University of Alberta

Sustainable mine reclamation and landscape engineering

by

Gordon Thomas McKenna ©

A thesis submitted to the Faculty of Graduate Studies and Research in partial fulfilment
of the requirements for the degree of Doctor of Philosophy

in

Geotechnical Engineering

Department of Civil and Environmental Engineering
Edmonton, Alberta
Fall 2002

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The undersigned certify that they have read, and recommend to the Faculty of Graduate Studies and Research for acceptance, a thesis entitled "Sustainable mine reclamation and landscape engineering" submitted by Gordon Thomas McKenna in partial fulfilment of the requirements for the degree of Doctor of Philosophy in Geotechnical Engineering.

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DATE: July 31, 2002

Dedication

To my lovely wife, Yvonne.

Abstract

Since its beginnings thirty years ago, mine reclamation practice continues to evolve. To determine the current state of practice for closure planing, landscape design, and to observe reclaimed landscape performance, 69 mines were visited. Reclamation, though generally well done, seldom satisfied stakeholders or regulators – few sites have received reclamation certification or been returned to the original owner. Until processes for setting realistic goals, multidisciplinary landscape design, and equitable transfer of residual liability are developed, mining companies will not achieve successful reclamation – mining will remain a terminal rather than temporary land use.

While most reclaimed areas of most mines exhibit good landscape performance, several shortcomings in the state of practice are clear. The use and rigor of surface-water hydrology design is lacking. Performance of slopes with erodible substrates, the high costs of trafficking soft tailings areas, and errors in predicting end-pit lake filling are particularly troublesome. Designs and regulations that accommodate the dynamic nature of landscapes are uncommon. Poor landscape performance often relates to fluxes (of ions, water, sediment, nutrients, etc) that are unanticipated or outside expected ranges or more commonly, simply fail to achieve unrealistic objectives.

Landscape engineering is introduced to help alleviate these shortcomings. It focuses on setting and achieving more realistic goals through inclusions of traditional engineering methods. Work is multidisciplinary and involve teams of specialists.

To demonstrate the technical side of landscape engineering, two studies were performed. In the first, the effects of uncertainty in substrate hydraulic conductivity were demonstrated with a database of 800 hydraulic conductivity measurements of oil sand tailings sand. Simple

geostatistical tools such as the coefficient of variation, upscaling, and quantifying spatial variability are demonstrated and several design scenarios described. The second study involves predicting erosion rates of fine-grained fills. Results from the laboratory, field, and the literature indicate erosion rate predictions, even under ideal conditions, are generally only accurate to within one order of magnitude. Both the studies highlight the need to estimate common landscape fluxes, their impact on performance, and the need to deliver robust designs and institutional mechanisms that allow for inherent limitations in predicting long term landscape performance for large or complex mining landforms and landscapes.

Preface

This research has been funded and supported by Syncrude Canada Ltd, operator of oil sands surface mining operations in Northeastern Alberta, Canada. The author is a fifteen-year employee of Syncrude and a member of Syncrude's Closure and Reclamation Team which is responsible for research into, and design of, the Syncrude lease-closure landscape. Thus the focus of this research is on issues and methods that can affect the successful landscape engineering with examples from the oil sands region.

The work has benefitted from active participation by the Department of Civil and Environmental Engineering of the University of Alberta which has played a major role in the ongoing development of the oil sands. The research also benefited from a large number of Syncrude staff and their consultants. This work has also received input from numerous people from mines in Canada and the United States, international consultants, and regulators who are interested in furthering our ability to rationally design, construct, reclaim, close, abandon, and regulate mines.

Acknowledgements

I am in debt to the many people and organizations who have contributed to the work and wish to acknowledge their valuable input. Many of the ideas presented in the thesis come from lengthy discussion with the following people over the past eight years.

For providing direction and mentoring, my thesis supervisors, Dave Sego and Nordie Morgenstern. Richard Dawson is thanked for coming to many of the mines with me, and sharing his insights, ideas, and providing encouragement. Ted Lord, Howard Ellis, Wayne McKee, and Bruce Friesen are thanked for providing their support throughout the project. In the field, Gerry Cyre and Victors Swain's Dentor Enterprises crew were crucial.

Syncrude Canada Ltd and its employees are thanked for providing support of this work over the past seven years. Bob Shaw, John Clark, John Oxenford, Paula MacGillivray, are thanked for their support. My landscape and reclamation colleagues at Syncrude, who have worked these issues and participated in many discussions and debates, have helped to form these conclusions. These colleagues include Beat List, Bill Shaw, Bob Cameron, Brad Strueby, Brent Parks, Bruce Friesen, Clara Qualizza, Dave Hardisty, Earl Anderson, Gord Livingstone, Graham Cuddy, Janelle Ducharme, Jonathan Matthews, Marie Keys, Martin Fung, Mike MacKinnon, Mike Rogers, Rick Lahaie, Ron Pauls, Steve Gaudet, and Terry van Meer.

For providing their time, openness, and insight during tours of their mine sites: Alex Jakubick, Bill Mitsch, Brent Hartley, Cam Bateman, Don Sheeran, George Hopkins, Glen Hall, Gord Livingstone, Horst Schor, Ian Horne, Jim Lant, Laurie Healey, Marty Puro, McCoy, Mike Aziz, Nan Davé, Richard Dawson, Roger Berdusco, Ron Jones, Ross McArthur, Sam Cho, Steve Janesewski, and Steve Tuttle.

The following companies are thanked for providing access to their sites and sharing their information: Atlas Historic Society, BHP Minerals, Falconbridge, Fording Coal, Highland Valley Copper, Imperial Metals, INCO, Laguna Construction Company, Lee Ranch, Luscar, Manalta Coal, MK Reclamation Co., Navajo Nation, Noranda, Ohio State University, Pittsburgh & Midway Coal Mining Company, Placer Dome, Rio Algom, Seven Industries, SF Phosphate, Shell, State of Utah AML, Suncor Oil Sands, Syncrude Canada, Taseko Mines, Three Sisters Resorts, Transalta Utilities, Westmin Resources and WISMUT.

The following people are thanked for their input into the study: Ahmet Mermut, Ann Smreciu, Andy Robertson, Bill Stolte, Bruce Dean, Bruce Rains, Clayton Deutsch, Dale Shuttleworth, Dan Lovbakke, Dave Cruden, Dave Devenny, Dave Horsfield, David Chanasyk, David Laughton, David Morrey, Derrill Shuttleworth, Dianne Trach, Ed McRoberts, Femi Adi, Derald Smith, Don Scott, Don Sheeran, Frank Munshower, Gerry DeSorcy, Hal Hamilton, Horst Schor, Ian Muirhead, John Errington, John Gadsby, Karvin Kwon, Larry Roy, Lee Barbour, Les Sawatsky, Marten Ingen-Haus, Peter Nichols, Scott Fisher, Sean Ennis, Steve Hrudy, Terry Macyk, Tim Eaton, Syncrude's Land Restoration Technical Advisory Panel, and Syncrude's Geotechnical Review Board.

In the field and the laboratory, I was fortunate to receive support for the following people: Catherine Stasiuk, Chris Grenier, Cindy Cusick, Dave Parson, Gerry Cyre, Julian Gan, Kent Wong, Moir Haug, Peter Ngo, Ryan Krushnisiuk, Steve Gamble, Tashia, Victor Swain, and Wayne Evansiuk.

And most importantly, this work could only be accomplished with the ongoing support and encouragement of this work by my wife, Yvonne, and our two fine young sons, Andrew and Matthew. Thank you.

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List of symbols and abbreviations

Chapter 6 – Tailings sand permeability

AE	analytical error (cm/s)
CoV	Coefficient of variation of hydraulic conductivity (%)
GE	geologic error (natural variability) (cm/s)
c	empirical scaling coefficient (dimensionless)
d_{10}	10th percentile grain-size diameter (mm)
e	average annual percolation rate (cm/s)
$\gamma(h)$	semivariance at lag distance h (cm^2/s^2)
$\gamma(0)$	nugget variance (cm^2/s^2)
h	lag distance (m)
h	height of water table (phreatic surface) above datum (base of aquifer) (m)
h_d	height of water table at ditch or pipe invert above datum (m)
h_{max}	height of water table at maximum location (midway between ditches or pipes (m)
i	average annual percolation (percent of total precipitation (%)
k	hydraulic conductivity (cm/s)
k_s	hydraulic conductivity of surface tailings sand (cm/s)
k_h	horizontal hydraulic conductivity (cm/s)
k_i	ith hydraulic conductivity (cm/s)
k_v	vertical hydraulic conductivity (cm/s)
k_h/k_v	ratio of horizontal to vertical conductivity (dimensionless)
k(v)	hydraulic conductivity as a function of scale (test) volume (cm/s)
L	horizontal distance between drainage ditches or pipes (m)
$(\log k)_{avg}$	average of the logarithm of hydraulic conductivities (geometric mean)
$(\log \sigma)_{avg}$	standard deviation of logarithm of hydraulic conductivity (cm/s)
μ	mean permeability (cm/s)
m	scaling exponent (dimensionless)
N	number of observations or elements
N(h)	number of pairs of data at lag distance h
p	power law scaling averaging exponent (dimensionless)
ME	measurement error (cm/s)
PE	instrument or sample preparation error (cm/s)
r	correlation coefficient (dimensionless)

R	ratio of unit costs of primary versus secondary drainage (dimensionless)
R(h)	Moran's statistic (autocorrelation coefficient) at a given lag distance (dimensionless)
σ, σ^2	standard deviation, variance of hydraulic conductivity (cm/s, cm^2/s^2)
TE	total error (cm/s)
v	scale volume (m^3)
v_L	volume above which permeability is scale invariant (m^3)
V	target volume for power law averaging (m^3)

Chapter 7 – Soil erosion

A	first erosion rate coefficient (applied to average shear stress)
B	second erosion rate coefficient (applied to elapsed time)
C	third erosion rate coefficient (intercept)
c"	modified third erosion intercept ($c"=10^C$)
CEC	cation exchange capacity
S	average initial surface topographic slope gradient ($\Delta H/\Delta L$) of soil surface (%)
d	average depth of flow (mm)
EC	electrical conductivity (dS/m)
ESP	exchangeable sodium potential
ε	erosion rate ($g/m^2/h$)
γ	unit weight of water (9.81 kN/m^3)
L	Length of flume or gully (m)
Q	discharge rate (lpm)
N	Manning's roughness coefficient
R	hydraulic radius (m)
r^2	correlation coefficient
SAR	sodium adsorption ratio
t	time since beginning of test or since flow started (h)
τ	shear stress (Pa)
τ_{cr}	critical shear stress (Pa)
v	average water velocity (cm/s)
v_{cr}	critical velocity (cm/s)
w	average width of flow (cm)

List of closure and reclamation terms

This list is adapted from Syncrude Canada Ltd (2001) based on original work by Dave Devenny. Definitions vary by jurisdiction and discipline and continue to evolve.

abandonment: 1. A term used by regulatory agencies denoting custodial transfer. 2. Unilateral rejection of custodial responsibility for ongoing reclamation or remediation. This could be voluntary or involuntary as in the case of bankruptcy.

Aboriginal traditional land uses: Refers to established uses by the Aboriginal peoples (gathering, hunting, trapping, transportation and spiritual use).

closure: The point after shutdown of operations when reclamation and remediation activities are satisfactorily completed, regulatory certification is received and transfer to the next custodian is possible.

closure objective: Corporate objectives to be achieved by activities undertaken to reclaim and restore land disturbed by development activities. Logically the objective would be responsible, economical reclamation to a condition that qualifies for a timely unconditional reclamation certificate.

closure obligation: Corporate obligation to restore disturbed land to a condition equal to or better than that which existed before development occurred. The obligation is often interpreted to mean to a state acceptable to regulatory agencies and key stakeholders.

closure path: A set of reclamation activities undertaken to achieve satisfactory closure. All details may not be known at the start of a project and proposed activities may change as new knowledge suggests a more appropriate approach.

closure plan: The closure plan describes the technical measures and planning programs to be undertaken for the active decommissioning, rehabilitation and ultimate closure and release of a mine site.

custodial transfer: The transfer of reclaimed land, with reclamation certification in place, to a subsequent land manager or user who takes full responsibility for ongoing sustainability of the landscape and its end land uses.

deed of custodial transfer: Documentation that reclamation or remediation objectives have been met and custodial transfer has been accepted by the transferred from the transferor. The reclamation certificate.

design for closure: Applying integrated planning through all phases of a project to meet the requirements for successful closure. Project phases include initial planning, development, operations, ongoing and final reclamation. Considerations include an economical and environmentally responsible approach to mine layout, ore handling, waste management, water management, backfilling and reclamation.

development: The stage of a project after exploration that involves all activities to initiate mining, and includes construction of infrastructure, plant facilities, temporary water diversion, etc. For an open pit mine development involves site clearing (mine and disposal area), surface-water diversion and control, basal water depressurization, overburden removal, installation of support infrastructure (power supply, access roads, crushers, pump stations etc.)

due diligence: Taking appropriate, responsible and defensible action.

ecosystem: An interacting system of all living organisms in a circumscribed region of similar characteristics, and the non-living substrate, nutrients, energy and other environmental components.

end land use (or land use): The particular use or uses planned for each reclamation unit, not necessarily identical to predevelopment uses

enforced closure: Premature closure of a mine or mineral processing plant prior to the end of planned life of the operation due to factors such as financial bankruptcy, financial viability, political instability, technical problems.

extreme events: Extreme cases of natural phenomena such as floods, severe earthquakes and heat waves which may occur at certain statistically determined time return intervals, and which tend to have a particularly detrimental affect on the environment (both natural and artificial).

geographic information system (GIS): Refers to a computer-based system for the storage, management, processing, analysis, update and output of spatial data.

groundwater: That part of the subsurface-water that is in the zone of saturation.

hazard: A condition with the potential for causing an undesirable consequence.

hectare: A metric unit of area equivalent to 10,000 square metres or 2.24 acres. There are 100 hectares in a square kilometre.

in situ: In the ground, undisturbed, in its original place.

infrastructure: On and off-site facilities required to support development. Examples of on-site facilities for an oil sands mine include access roads, buildings (process facilities, service buildings, office, warehouse, camp), water and sewage systems, waste storage facilities, roads emergency response facilities etc. External facilities include roads, railroads, airports, , power supply (electrical and natural gas) and related transmission facilities, product pipelines, communication linkages, employee housing etc.

intensive recreation: Refers to high-density recreational use such as developed staging areas and camp and picnic grounds, and other sites or areas requiring continuous recreational management and services to maintain recreational opportunities.

land capability: The ability (unaltered by a level of future management inputs, activities or alterations) of land resources to support a given land use on a sustained basis, based on physical, chemical, and biological characteristics of the land including topography, drainage, hydrology, soils, and vegetation.

landform: A distinctive topographic feature. It may be created by natural or artificial processes. Major landforms include - mountain, plain, plateau, valley. Landforms include: hill, valley, slope, esker, dune. Taken together landforms make up the surface of the earth.

landform grading: Constructing landforms to meet specific performance goals that could include: aesthetically pleasing, stable slope angles (not too steep), direct surface drainage to desired exit channels etc.

landscape: The composite of all visible features including land, water and vegetation, and its interacting ecosystems.

land use: Use of land (or water areas) for a specific purpose. Examples: traditional aboriginal uses, grazing, commercial forestry, recreation, agriculture, industrial.

land use –sustainable: Use or uses that can be sustained indefinitely with the resources provided (including fiscal resources), or which can be generated by the use. Renewable resources (forestry, hydropower, commercial recreation etc.) are examples of uses that may be self funding sustainable uses. Subsidized (from an adequately sized trust fund) managed parkland or recreation land are examples of fiscally augmented but sustainable use.

land use - self sustainable: Use that is sustained by natural processes and does not require actions by man. For example: unmanaged wilderness or natural reserve use. (no maintenance required). land use - passive care sustainable use. Use which requires infrequent, periodic and low effort by humans to maintain the sustainable use. For example: rangeland use requires rangeland management. (passive care and maintenance required)

land use active care sustainable use: Operation and maintenance of a water collection and treatment plant to remove pollutants from discharge. (Active maintenance is required)

landscape performance: Measured performance of the landscape against declared goals

long term stability: 1. Stability of a reclaimed land surface against significant erosion by wind, water and the forces of gravity. For example: stability against wind blow-outs, sheet erosion, gully formation, stream bed migration, landslides, etc. 2. Sustainability of surface vegetation. 3. Standards may be set to establish performance criteria and to monitor relative stability.

maintenance-free: Reclaimed land that is as sustainable as the original landscape without human intervention.

management block: Distinct increments of reclaimed land, composed of one or more reclamation units, for which reclamation certification, and potentially custodial transfer, can be pursued.

landscape unit: A reclaimed area with distinctive characteristics. (landform shape, drainage, surface soil, vegetation etc. A group of adjacent landscape units together make up the management block described earlier.

mine closure: Permanent cessation by a company of operations at a mine or mineral processing site.

mine development: Preparing a mine site for ore extraction. See "development" above.

mine land reclamation: Returning land disturbed by mining to a state acceptable for an approved land use.

mineral deposit: A zone of material that may or may not be economic to mine.

mining lease: A legal contract for the right to work a mine and extract the mineral or other valuable deposits from it under prescribed conditions of time, price, rental, or royalties.

mining: Activity whose purpose is the extraction, concentration, smelting of economic minerals from a mineral deposit. It includes exploration, development of mineral deposits, constructing the mine and mining, (extracting and processing the ore or tailings).

open pit: A surface mine, open to daylight, such as a quarry.

operational water release: A controllable and treatable, point source discharge to the regional river system that, in an untreated state, could potentially cause an off-site impact.

operations: All activities at a mine prior to mine closure, which include construction, ore extraction, and product processing.

ore: A deposit which, under current conditions, contains economically recoverable hydrocarbon. Considerations - deposit geometry and continuity, grade, waste/ore ratio etc.

orebody: A contiguous body of ore.

ore reserves: The portion of a mineral deposit that can be profitably mined. Use of this term implies both an appropriate detailed knowledge of all the geological, engineering, economic and environmental parameters that might affect on profitability of the operation. For a new mining project or for the mining of new zones in an existing mine, a formal feasibility study is conducted to evaluate all parameters of the project.

plan: A way of proceeding to accomplish project goals. A mine plan should reflect a well designed and considered series of activities vs time to clear overburden, control surface-water, depressurize basal aquifers, mine ore and waste, transport ore and dispose of waste and progressively reclaim the site as the mine advances. The plan identifies the quantity of ore and waste as well as equipment and manpower needs vs time.

planning: Detailed design of mining activities leading to the mine plan described above.

passive care sustainable use: Use which requires infrequent, periodic and low effort action by people to maintain the sustainable use.

perpetual disruptive forces: Perpetual disruptive forces are generally slow acting natural or human-induced processes which work over an extended period of time.

planner: The person who executes a mine plan – usually a mining engineer.

post closure: The period after all decommissioning and demolition activities have ceased during the closure period. This generally signifies the period of active and passive rehabilitation leading to site release.

predevelopment: Site conditions that existed before development commenced.

production: That which is produced or made; any tangible result of industrial or other labour. The yield or output of a mine, metallurgical plant or quarry.

progressive rehabilitation: Rehabilitation that is ongoing over the life of the mine.

project closure: Completion of all reclamation and remediation measures to the satisfaction of the succeeding custodian and the steward.

project initiation: Initiation of land disturbance; assumption of custodian responsibility for reclamation or remediation of the disturbed land by the current tenant.

reclamation: Actions intended to return the land surface to an equivalent undisturbed condition, usually involving replacement of topsoil and vegetation on reconstructed land.

reclaimed land (or area): Disturbed areas with the land capability returned to a status equivalent to or better that predevelopment, with or without reclamation certification granted.

reclamation certification: Agreement received from a regulatory agency that a management block has been reclaimed to an acceptable land capability as proven by performance monitoring over a required period of time.

rehabilitation: The return of disturbed land to a stable, productive and self sustaining condition, after taking into account beneficial uses of the site and surrounding land.

remediation: Actions intended to improve disturbed land to achieve a desired land use. Remediated land is disturbed land that has been developed to an alternative desired land use.

resloping: Modifying an existing slope to enhance its stability.

restoration: The return of disturbed land to its former use.

riparian: Pertaining to or situated on the bank of a body of water like a river

risk: exposure to a hazard, characterized by probability of occurrence and severity of consequence.

safe: The condition of a closed mine site such that the risk of adverse effects to people, livestock, other fauna and the environment in general has been reduced to a level acceptable to all interested parties.

self-sustainable use: Use which is sustained by natural processes and does not require actions by people.

site reclamation provision: Financial assurance provided to fund future site reclamation

site release: Relinquishment of the site after closure once all requirements set in the closure plan or by various authorities have been met. This is generally to an alternate land use.

soil: 1. Earth material that has been so modified by physical, chemical and biological agents that it will support rooted plants. 2. All regolith (loose incoherent surficial material that covers bedrock)

soil capability: Ability of soil to support growth.

stable/stability: measure of the relative ability of a land surface to resist erosion or of established vegetation to persist.

stakeholders: Individuals, groups and regulatory agencies with a substantive interest in closure of disturbed land as a land manager or land user.

stockpile: Material dug and piled for future use.

stripping ratio: A dimensionless ratio: quantity of overburden removed to access an ore body/quantity of ore recovered

succession: A series of dynamic changes by which one group of organisms succeeds another through stages leading to a climax community.

sustainable development: 1. A process of change in which the exploitation of resources , the direction of investments, the orientation of technological development, and institutional change are made consistent with future as well as present needs. 2. Development that is sustainable for the long term without adverse environmental effects.

sustainable landscape: A landscape that survives extreme events and natural cycles of change, without suffering environmental impacts any more severe than that of the natural environment.

sustainable use: Use or uses which can be sustained indefinitely with the resources provided (including fiscal resources), or which can be generated by the use. Renewable resource uses (forestry, hydropower, commercial recreation, etc.) are typical examples of uses that may be self-funding sustainable uses. Subsidized (from an adequately sized trust fund) managed parkland or recreational use are examples of fiscally augmented but sustainable use.

tailing dam: Structure designed to contain mining tailings and wastewater.

tailing pond: Place for storing mine tailings and other residues resulting from ore processing and mining.

terrace: Relatively flat horizontal or gently inclined surface, bounded by a steeper ascending slope on one side and by a steeper descending slope on the other side.

terrain unit: A unit of land that incorporates a predominant combination of landform and surficial geology, including shape, slope, aspect, and surficial materials

topography: The physical features of the surface in an area.

topsoil: Fertile dark coloured surface soil.

uncontrolled events: Events with very low probability of occurrence, including major earthquakes, meteorites, climatic change, unplanned human activity, sabotage or stakeholder changes.

undisturbed land: Land materially unchanged by human activity.

upland ecosystem: Portions of reclaimed land characterized by: a) terrestrial vegetation, including but not limited to trees, shrubs, grasses, and forbs, and b) a rooting zone that is dry for the majority of the year.

walk away: No additional monitoring or maintenance activities are required after rehabilitation work has been carried out.

wetland ecosystem: Portions of reclaimed land characterized by: a) open water, or b) a rooting zone that is wet for long enough periods that aquatic or semi- aquatic vegetation is present.

wetlands: Any land saturated with water long enough to promote wetland or aquatic processes as indicated by poorly drained soils, hydrophilic vegetation and various kinds of biological activity that are adapted to a wet environment..

Chapter 1

Introduction

Mining has always been, and will always be a critical element of civilization but is presently under siege in most industrialized nations as being a dirty polluter of the environment (e.g., Mining Engineering, 2000). The general sympathy that extends to miners does not extend to mining companies (Hinde, 2000). Much of this sentiment has been earned by the mining industry's historic performance – a legacy of abandoned, unreclaimed sites that present hazards to people, fish, and wildlife, and leave the land more or less permanently scarred (e.g., Johnson and Miller, 1979; Judd, 2000). Once a significant and popular employer, efficiencies and technological change over the past 100 years has caused the proportion of the Canadian employment population involved in mining to decline to only 0.8 percent (Statistics Canada, 1999). Despite large investments in reclamation and development of sophisticated reclamation technologies, today's mining industry is still suffering the lingering effects of this historic legacy (Fredricksen and Jones, 2001). Mining is becoming less and less popular and many would like to see it eliminated. Homer-Dixon (2000) points out, "The idea that we can get along without natural resources is now widespread in rich countries…it will come to be seen as one of the greatest fallacies of our time."

This thesis explores the current state of practice of mine reclamation with a focus on closure planning, landscape design, and landscape performance. Based on visits to a wide variety of mines, it is argued that the current state of practice is not resulting in successful reclamation and that a more thorough approach is needed. Landscape engineering is introduced and demonstrated as a new multidisciplinary activity for planning, design, and creation of reclaimed landscapes to allow mining companies to economically achieve their social licence as temporary users of the land.

1.1 A brief history of mine reclamation

Prior to the Sixteenth Century, mines and quarries, with some exceptions, were primitive, usually small, and dominated by manual labour. Publication of Agricola's *De Re Metallica* (Agricola, 1530; Hoover and Hoover, 1950) marks the start of the era of modern mining. Mines typically disturbed only a few hectares and the loss of land use and off-site impacts were often small and unimportant to society and hence reclamation was not considered.

In the following centuries, the average size of mines increased. Starting in the 1940s, there was development of large earth moving equipment and modern accounting and investment methods that permitted an expansion into large mining activities. Most open pit mines today disturb a few thousand hectares, the largest disturb tens of thousands of hectares – the size of modest cities. And as the economics of moving vast amounts of the earth improved, lower grade ores are mined – typically less than five percent of the rock and soil moved is ore (and often much less than one percent), the rest is waste. More than ever, mining is an exercise in waste management (Hutchison and Ellison, 1992).

Coincident with the enlargement in mine disturbances over the past five decades, has been a change in focus from "taming the environment" to one of "protecting the environment" (Cronon, 1995). Perhaps ironically, the wealth created in part by mining, has led to increased concern for the environment by society. The impacts of primary industries (agriculture, forestry, fishing, mining) on the environment are under increasing scrutiny. Regulations requiring mine reclamation started in the 1960s. A passage in the SME Mining Engineering Handbook indicates the state of practice of mine reclamation just 30 years ago:

> *In a region of sparse population and arid conditions it may be acceptable to leave the mine site as is. Should a valuable natural resource, such as water, exist in this same area, it may be desirable to grade unconsolidated material to a stable contour to prevent water pollution. At the other extreme, where the site under arid conditions is near an area of high population density, complete backfilling may be desirable.*
>
> *(Cummins and Given, 1973)*

As increasing population exerts ever-increasing pressures upon the finite land base, society recognizes the need to balance the environmental disruption and landscape changes caused by mining. In return for being permitted to reap the mineral wealth from the land, the mining industry has, in essence, formed a social contract with society – that after mining, using some of the profits from mining, the land will be restored to a safe and useful state. Miners have adopted a mantra of "temporary use of the land" (e.g., Morrison, 2001). This social contract forms the basis of government legislation, policy, and regulations that attempt to form a more clearly defined obligation on the part of the mining companies.

Developed in the early 1970s, the strategy of "designing for closure" was adopted for new and expanding mines in the 1990s (Gadsby, 1996) and formalized by requirements for submission of mine closure plans (e.g., Ontario Ministry of Northern Development and Mines, 1996). The industry is in a new transition period, with only the newest mines having started with a formal closure plan, and most of the techniques for designing for closure (especially implementing these designs over the life of a mine), are still maturing.

1.2 Some significant influences on mine reclamation practice

Over the past 30 years, significant events and activities related to mining landscape performance have shaped present regulation and practice. These include

- The Aberfan disaster of 1966 in which a coalmine spoil tip liquefied and flowed into an adjacent mining village, killing 28 adults and 116 children in school (Miller, 1974). This event lead to the requirement for civil engineering design of waste impoundments and tailings and the rise of mine waste geotechnique (e.g., Dawson, 1994).
- In the 1960s and 1970s, the historical legacy of mining without reclamation or due regard for the environment became a major issue and resulted in considerable efforts in describing and inventorying problems (US Department of the Interior, 1967; Johnson and Miller, 1979) and the adoption of new regulations.
- The Stava tailings dam disaster in Italy in 1985 killed 268 people and marked the recognition of director liability for mining environmental performance (Chandler and Tosatti, 1995).

- Reclamation of uranium tailings in the United States (Caldwell, 1989), Canada (Elliot Lake Uranium Mine Tailings Areas Environmental Assessment Panel, 1999), Germany (Federal Ministry of Economics, 1995), Australia (Waggitt, 2000) and elsewhere started to identify the nature and limitations of designing for long term performance and the necessity of long term maintenance for many sites.
- In 1988, the Mine Environmental Neutral Drainage program started and over the following decade investigated and provided design guidance for preventing and controlling acid rock drainage from mines (MEND Secretariat CANMET, 2001). This Canadian program has had world-wide impact.
- The 1992 Summitville incident, where a large active mining project was suddenly abandoned, crystalized the need for better protection of the public purse by the government (Plumlee and Edelmann, 1998). During this time, it has become a requirement to show environmental liability as part of generally accepted accounting practices, and for mining companies, this has started to highlight their exposure to large and increasing reclamation and closure costs (Canadian Bankers' Association, 1991; Carlos Da Rosa, 1999).
- In 1996, Ontario Guidelines for mine closure planning (Ontario Ministry of Northern Development and Mines, 1996) became available, and have been employed (with modification) in countries around the world.
- The environmental consequences of recent tailings dams failures, including Omai (Guyana), Marcopper (Philippines), Los Frailes (Spain), Baia Mare (Romania), and Martin County Coal Corporation (USA) has raised the public awareness of the potential environmental impacts of mining (East, 2000) and the effect of environmental incidents on a company's reputation and share price.
- The role of cumulative effects of multiple mines and industries in a region is forefront in some areas (Alberta Environment, 1999) indicating the need for more accurate prediction, control, and remediation of operational and long term fluxes of constituents of concerns and land disturbance not only at the landform and landscape scale, but also at the regional scale.
- The recent debate concerning the role of prediction in formulating public policy on the generation of anthropogenic greenhouse gasses (and their role in climate change) has included scrutiny of science's ability to predict future performance of complex environmental systems (e.g., Sarewitz et al., 2000). Recognition of the inherent limitations of prediction is perhaps the start of a shift away from a reliance on prediction almost exclusively and towards creation of institutions for control and management of potential outcomes and to deal with

residual uncertainties. Recent recognition of the need for long term institutional control and maintenance of many reclaimed minesites reflects a similar trend in the mining industry.

1.3 Objectives

The objectives of the thesis are broadly:

- To determine the current status of closure planning, closure performance, landscape design, mine reclamation, and reclaimed landscape performance and how well these efforts and outcomes support mining companies and the mining industry
- To determine how engineering can contribute to goal setting, design, construction, monitoring, and maintenance of landscapes to provide greater confidence concerning landscape performance and provide reasonable assurance of meeting clearly defined goals
- To demonstrate levels of parameter and model uncertainty using real examples (permeability and erosion rates), and show the impact on the uncertainty of predictions of long term landscape performance
- To attempt to answer the question: “How well can we predict long term landscape performance?” and develop methods, tools, and strategies to accommodate uncertainty through more thoughtful design and construction and through adoption of other institutional mechanisms
- To develop and introduce the discipline of Landscape Engineering, describe the current state of practice, describe unifying technologies, set it in a historical context, compare it to existing disciplines, and predict its evolution.

1.4 A guide to this thesis

To gain a first hand, and up-to-date assessment of the state of mine reclamation and closure planning practice, and to evaluate reclaimed landscape performance, the author visited 69 mines in North America (with a focus on western Canadian mines) in the late 1990s. Chapter 2 describes the methods, the mines visited, and observations on mine closure planning and experience and attempts to answer three questions: What is the current state of practice of mine closure planning? How are goals set and how well are they met? What happens when a mine closes? Chapter 3 provides an overview of the present state of practice of landform and landscape design and the landscape performance of reclaimed mine land and attempts to answer three more questions: How well is each discipline contributing to landscape performance? How well is each constructed terrain unit type performing? How well are monitoring and maintenance being performed? Chapter 4 describes what elements are required for "successful reclamation" and crystalizes the need for a more formal approach to landscape design and reclamation. It attempts to answer the questions: How can successful reclamation be defined? What are the elements of successful reclamation? How well are mining companies achieving successful reclamation?

Chapter 5 describes the new discipline of Landscape Engineering as an example of a more formal approach to meet the ideals of successful reclamation. Landscape engineering is a framework and a toolbox of largely engineering philosophies and activities to help mining companies to achieve successful reclamation by setting reasonable goals and focussing design, construction, reclamation, and maintenance activities to achieve these goals. It is framed in terms of traditional engineering activities but is a multidisciplinary exercise, drawing on expertise of mine planning, geotechnical, groundwater hydrology, surface-water hydrology, soil science, vegetation science and other specialties (such as geochemistry, wildlife, forestry and agronomy) as needed for specific situations or sites. This chapter attempts to answer these questions: What is landscape engineering? What is the need? What is the current state of practice? What are the unifying technologies? How does it compare to other disciplines? How is it likely to evolve?

Beyond goal setting and design, a central activity for landscape engineering is the design of landscapes to accommodate fluxes – water, ions, sediments, etc. Prediction of these fluxes is essential, but because the systems are complex and dynamic, estimates are often only accurate to within an order of magnitude, even under good conditions. To investigate and demonstrate such activities, two laboratory / field programs were undertaken.

Chapter 6 describes the geostatistics of tailings sand hydraulic conductivity based on over 800 measurements at various scales and spatially at Syncrude. It provides a simple set of geostatistical tools and indicates the need to consider spatial variability and scale effects in design of landscapes and landforms. It examines the role of uncertainty in hydraulic conductivity on landscape design and performance. It attempts to answer these questions: What is the variability of tailings sand permeability? How does this variability impact design and performance? How can design accommodate this variability? What are some useful geostatistical tools to deal with this variability in design and operation?

Chapter 7 provides details of a laboratory flume test to predict rates of erosion of dispersive clay fills. Examination of the literature and the results from the testing highlights the general uncertainty in such predictions and methods of landscape design to accommodate this uncertainty are presented. This chapter attempts to answer four questions: How well can erosion rates be predicted? Can a laboratory test allow accurate prediction of field erosion? How does water chemistry affect erosion rates of a dispersive clay? How can uncertainty in erosion rates be accommodated through thoughtful design and long term declining maintenance?

Chapter 8 provides some overall conclusions and suggested areas for additional research and development. Appendices follow Chapter 8. Appendix A is a detailed report of the 69 mine visits. Appendix B has a checklist for landscape performance risk assessment. The tailings sand permeability database is featured in Appendix C and the calculation methods in Appendix D. The erosion flume trial database is presented in Appendix E.

This thesis is presented in "papers format" – each of the chapters is written to stand alone in a form publishable in a journal. This means that each chapter has its own reference list, and the reader may notice some repetition from previous chapters.

The main contributions of this thesis are:

- the description of the current state of practice in mine reclamation, landscape design, closure planning, and mine closure, highlighting that current practice seldom results in reclamation certification by regulatory agencies or transfer of the reclaimed land back to the crown or state – a failure of the mining industry to fulfil its social contract of being a temporary use of the land
- descriptions of reclaimed landscape performance by discipline and by anthropogenic terrain unit, highlighting areas of good performance, and areas of poor performance including surface-water hydrology and tailings reclamation
- a definition of "successful reclamation" and its elements
- development of the new discipline of landscape engineering to address the challenge of achieving successful reclamation, and comparing and contrasting its scope and development with other related disciplines

- measurement of over 800 oil sands tailings sand permeabilities, describing their variability, and describing the data with a geostatistical framework with simple upscaling and spatial variability tools, and using a simple landscape design example, showing how to overcome the inherent uncertainty in substrate permeability through use of the observational method
- creation and calibration of a laboratory erosion test to predict rill and gully erosion of landforms constructed from clay fills, quantification of the large degree of uncertainty in erosion predictions, and description of goal setting, design, and maintenance strategies to accommodate this wide range of uncertainty.

As identified in this thesis, the major obstacles facing the mining industry in achieving successful reclamation are threefold:

- the gulf between the goals agreed to by mining companies and their institutional and technical ability to achieve these goals,
- the lack of appreciation of the uncertainty in long term landscape performance and how to accommodate this uncertainty in design, and
- legal barriers to transfer of residual liabilities for future performance to subsequent land custodians such as the crown or the state.

Landscape engineering is offered as an activity to address goal setting and the engineering elements of design, construction, assessment, and maintenance of reclaimed landscape to help deal with the first two obstacles. Changes in environmental policy and legislation at federal and provincial levels, especially regarding "polluter pays" legislation, to allow open and equitable transfer of environmental liability is needed to address the third obstacle. One can remain hopeful that a solution that protects the environment, the public purse, and the long term viability of environmentally sensitive industries like mining can be forged.

It is hoped that promotion of findings from the mine visits along with the concept of landscape engineering may help to provide the mining industry with the tools it needs to improve its environmental performance, better fulfil its social obligations, and better weather the current anti-mining period.

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Chapter 2

Observations on mine closure planning and experience

2.1 Introduction and background

The mining industry and its regulators are starting to recognize that reclamation and closure need to be planned and integrated throughout a mine's life. *Successful reclamation* is reclamation that supports the mine's activities, meets agreed upon goals, includes progressive certification and transfer of liability, and can be reasonably assured of providing good long term landscape performance. Two elements of successful reclamation are closure planning and landscape design; two important measures are closure performance and landscape performance.

Closure planning involves planning effectively for the after-mining landscape – all activities required before, during, and after the operating life of a mine that are needed to produce an acceptable landscape economically. Closure performance refers to the activities near and after mine closure and how well activities listed in the closure plan are carried out.

The case can be made that a mine begins to close the day it opens. Decisions made during the mine planning and development phase – and even earlier, during the exploration phase – have profound effects on the ultimate closure plan, its cost, and the resulting landscape performance. These decisions need to be made within a framework of closure planning to realize successful reclamation.

To learn the state of practice in closure planning and performance and landscape design and performance, 69 minesites in Canada, the United States, and Germany were visited. Details from the visits are presented in Appendix A.

This chapter describes the study methods, overviews the literature, and describes findings related to closure planning. It lists typical closure goals and difficulties in, and solutions for, their achievement. Closure performance (especially decommissioning, certification, and custodial transfer) is summarized, highlighting the disappointing performance when a mine closes and identifies problems such as a "closure information gap", a "certification barrier" and a "liability trap" that together have lead to a "custodial transfer barrier."

While the report focuses on the shortcomings that became obvious during the mine visits, the mining industry can generally take pride in its work – most of the reclaimed areas are performing well, and have many appealing features. Reclamation methods and closure planning are well developed and a normal part of modern mining. Mining personnel are qualified and committed to doing a good job. As described below, the next focus is procedural – setting more realistic goals, establishing design procedures to achieve those goals, and changes in legislation to allow equitable transfer of land back to the state.

2.2 Methodology

Sixty-nine minesites were visited between 1996 and 2001 (Figure 2-1). Some mines were chosen in consultation with independent consultants and mine regulators – many of these because the mines were in or near the closure phase. Many were chosen for their climatic location, being near the author's workplace (Syncrude) and thus most are in Western Canada. Some were visited during public tours as part of reclamation conferences, and others were visited as brief stops on the author's vacations. Though far from a random sample, the sites visited provide a breadth of mining methods, ore types, regulatory jurisdictions, geology, climate, age and of sizes disturbance and reclamation (see Table 2-1 and Figure 2-2). The number and diversity of sites allows general conclusions to be drawn.

Each mine tour lasted several hours and involved visiting most areas of each minesite. A long checklist was used to make observations and ask questions. Observations were supplemented with reports and handouts from the mines, government maps, and company and government Internet web sites. Most visits were enthusiastically hosted by the person responsible for reclamation at the mine.

2.3 Literature review

The literature on closure planning, and landscape design and performance is small and changes are occurring rapidly.

Requirements for closure plan submissions are largely based on Ontario's *Rehabilitation of mines: guidelines for proponents* (Ontario Ministry of Northern Development and Mines, 1996) tailored by each jurisdiction. A good example of government requirements for closure plan preparation is provided by Gouvernement du Québec (1997). Walters (1998) summarizes typical requirements.

Articles describing the merits of closure planning include: Australasian Institute of Mining and Metallurgy (1976), Newey and Lewis (1976), Bell (1989), von Oppenfeld and Hiser (1994), Feneng and Asabere (1995), McKenna (1996), Marcus (1997), McKee and McKenna (1997), Robertson et al. (1998), Carter (2000), Kunanayagam et al. (2000), Mchaina (2000), and Warhurst (2000). Recommended references that focus on case histories of reclamation and closure include Taylor and Fox (1978), Brown et al. (1992), Hamaguchi (1999), Aziz and Ferguson (2000), Phillips et al. (2000), and Battle Mountain Canada Ltd (2001).

Technical papers which deal broadly with design include those by North Dakota State University Land Reclamation Research Center et al. (1983), Australian Mining Industry Council (1987), Harwood and Thames (1988), McKenna and Dawson (1997), Morgenstern (1999), Eger et al. (2000) and Achari and Hettiaratchi (2001).

On estimating financial assurance and liability, there is guidance from Canadian Bankers' Association (1991), Saskatchewan Environment and Resource Management Industrial Branch (1996), Gouvernement du Québec (1997), Anderson et al. (1999), Brodie Consulting Ltd (1999), Kuipers (2000), and MacDonald (2000).

Reviews of mine reclamation performance include those by United States Department of the Interior (1967), Rowe (1979), Johnson and Miller (1979), Cardwell and Sanz (1985), Hutchison and Ellison (1992), Sengupta (1993), and Todd and Struhsacker (1997).

Broader issues of the philosophy of mining and the environment can be found in Cragg et al. (1995), Riley (1995), Earley et al. (1997), Cragg (1998), and McAllister et al.(1999). Examples of anti-mining literature on mine planning and the environment include Carlos Da Rosa (1999) and Dahlberg (1999). Numerous anti-mining Internet websites provide interesting study.

A review of the table of contents of three mining serials from 1999 to 2001 provides an indication of the role of reclamation and closure planning in the mining industry. In Coal Age, a trade magazine, only two percent of the articles related to reclamation and none to closure. About 15 percent of the feature articles in the CIM Bulletin and Mining Engineering Magazine were about reclamation, closure planning, or sustainable development. This level of representation in recent years attests to the importance and interest in closure activities by the mining industry. A similar percentage of talks at mining conferences deal with reclamation and closure and there are several well attended regional conferences, such as the BC Mine Reclamation Symposia and the Billings Land Reclamation Symposia, that deal exclusively with mine reclamation.

2.4 Closure planning

Closure planning activities

The first closure plans were prepared by a few mines in the late 1980s. Driven by regulatory requirements, most operating mines have now prepared a first-generation closure plan in the last five years – closure planning is becoming the norm for the mining industry. Figure 2-3 provides a summary of the status of mines visited and their closure planning stage.

Activities related to closure planning often include: preparation of detailed drawings of disturbed landscape, compilation of baseline information, discussions with regulators and stakeholders on end land use considerations, crafting of supporting research programs, and preparation of budgets and schedules. For a mine nearing closure, the closure plan takes the form of a decommissioning plan, and includes details and selection of mitigative technologies (especially for acid rock drainage) and other specific reclamation and closure activities.

A critical element of successful reclamation and of good closure planning is stakeholder involvement. Only nine mines had ongoing stakeholder consultation processes. Generally, mines do a poor job of ongoing, meaningful stakeholder consultation, and many would benefit from professional assistance.

A particularly useful consultation process involves forming a local committee to provide guidance to one or more mines in the region in their reclamation and closure activities with a focus on providing ongoing dialog with stakeholders and identifying the goals important to stakeholders. Island Copper (Marcus, 1997), Mount Polley (Mount Polley Public Liaison Committee, 2000), Alberta's oil sands mines (Alberta Environment, 1999), and the southeast British Columbia coalmines are examples of mines that benefit from such committees. Britton (1998) details models for public participation used at Island Copper, Brenda, and Sullivan mines.

The most important benefit of closure planning is identification of critical activities to achieve successful reclamation. Closure planning usually identifies areas of needed research. It also identifies planning constraints (and sometimes opportunities) especially identifying safe methods and locations for mine waste storage. These plans provide some assurance that the mine is not "painting itself into a corner" and provide a starting basis to estimate financial assurance levels – important to both mines and regulators. It also forms a base case against which future planning changes can be compared. Much of this work falls under the concept of "design for closure" introduced 30 years ago (Gadsby, 1996).

Most mines visited that had a closure plan had created it after years of operation. Many of the key decisions that would affect long term landscape performance were already made in the early days of the mine with little regard to closure. Many of these early decisions had negative impacts on performance, costs, and typically created the need for long term maintenance to meet closure goals and regulatory requirements.

Typical closure planning documents

Typical closure plans are 100 to 200 page documents that require several months to prepare and cost approximately $200,000. They are usually developed by the supervisor of the environmental department, or by a mining, environmental, or geotechnical consultant. They are submitted at the request of the regulatory authority and are used by the mine for life of mine costing.

The focus of reclamation and closure work is strongly correlated to the type of specialist who leads this work. The survey revealed that generally a third are biologists and foresters who tend to focus on revegetation. A third are physical scientists and engineers who tend to focus on stability and covering acid rock drainage dumps, and about a third are mine managers or former operations supervisors whose main focus is cost and schedule. At soft rock mines (coal and oil sands), reclamation and closure work is usually more integrated with the operation and is headed by reclamation specialists. At the hard rock mines visited, closure and reclamation activities are more often seen as extraordinary items, left until mine closure, and headed by managers and operations supervisors (perhaps because for many metal mines, historically, almost all disturbed areas remain active until closure when the manager's focus turns to closure issues).

Most closure planning documents share the same format:

1. Introduction
2. Predevelopment conditions
3. Mine operations explained
4. Landscape performance goals (and regulatory requirements)
5. Reclamation technologies and methods
6. Reclamation plans, balances, waste isolation methods
7. Long term monitoring and maintenance plans
8. Landscape performance prediction
9. Comparison of the performance prediction relative to the goals
10. Schedules and costs
11. Financial assurance

Closure planning stages

Most of the mines visited started operations with no closure plan. Mine staff develop their first closure plan at the request of regulators. This conceptual plan is detailed enough to be complete and provide assurance to stakeholders and regulators that at least one viable path to successful reclamation is feasible. This plan often uncovers costly deficiencies in existing mine plans – for example, poor placement of a particular waste dump or improper waste rock disposal that is creating or has potential for development of acid rock drainage.

The quality of closure plans varies widely. Common flaws of many plans is that they are overly optimistic and often rely on the positive outcome of a high-risk assumption – for example, that acid rock drainage will be self-remediating or that an unproven tailings technology will minimize disturbance footprints. Over-reliance on complex environmental models (biological, ecological, geochemical, groundwater) is also common. Surprisingly, most closure planning does a poor job of clearly identifying goals, and addressing operational and long term monitoring. Consideration of contentious issues such as post-closure maintenance is often avoided.

The financial situation, available technology, and mine plans change frequently so most mines update their closure plans about every five years. Only one operating mine visited had developed an updated (second-generation) closure plan.

Plans developed near the time of actual mine closure are the most detailed. These decommissioning plans contain specific designs to construct the closure landscape and decommission the facilities. They are based on the science and knowledge available at that time – there is usually little room for research or experimentation at this phase of a mine's lifecycle. Closure plans for abandoned mines are always decommissioning plans and are usually much simpler, more creative, and have more modest goals than those for operating mines. Much can be learned from these abandoned mines programs such as modest goals, innovative practices, hazard mitigation strategies, use of multidisciplinary teams, stakeholder communications, and cost effective solutions (e.g., Bureau of Abandoned Mine Reclamation, 1998; National Parks Service, 1998).

When site reclamation is complete, a reclamation certification application with supporting documentation is needed for submission to the government regulators. This application will have many of the same elements as a closure plan. Almost no mines have made such an application.

Integrating closure plans with activities during operation

Most jurisdictions now require a closure plan as part of the initial permitting process for new mines and as part of ongoing permitting of existing operations. Despite what would seem to be obvious benefits of integrating this plan with the operations, closure planning is generally only well integrated with mine operations at the decommissioning stage. The lack of integration during operation is often a significant barrier to successful reclamation.

At opening, mining companies are strongly focussed on immediate matters of securing the necessary permits, mine planning and site preparation. Because closure planning often highlights uncertainties or gaps in their reclamation plans, mines are often less willing to invest effort into closure planning activities during the initial stages of mine development. Few want to hear about mine closure as they are planning its opening.

Environmental costs (including reclamation) as a percentage of total mining costs are relatively small. The *uncertainty and magnitude* of environmental costs, though often high, is less important during operation compared to other mining uncertainties such as stripping costs, ore grades, mill recovery, and timely permitting. So long as the closure goals are technically feasible, their cost generally receives less internal scrutiny, at least until closure looms. This present attitude towards closure planning in the early stages seems fairly pervasive and is unfortunate. As mentioned above, most key decisions that affect reclamation, closure and landscape performance – siting of pits, dumps, tailings ponds, their geometries, and methods of characterizing and handling materials – would benefit from effective closure planning at this early stage of development.

During operation, short-term economics and meeting regulations usually govern decisions. Of necessity, minimizing haul distance and maximizing ore recovery dominate the mining culture. Existing closure plans are usually consulted if major changes to the mine plans are proposed, but otherwise these closure documents are usually treated as only fulfilling regulatory requirements and left on the shelf. Lack of ongoing integration is often disappointing or frustrating to staff, regulators, and stakeholders.

At the two operating mines where there was modest success in integrating closure planning and operations, there was support of senior management and a closure planning team composed of members from across the organization (including production, planning, engineering, environmental, management). There were also efforts to integrate efforts of different disciplines (namely planning, geotechnical, surface-water hydrology, groundwater, soils, vegetation, wildlife, and sometimes other people such as geochemists or water treatment specialists) on mine reclamation designs and closure planning.

Boundary issues

Often, regulatory compliance is measured at a boundary (lease boundary, permit boundary, disturbance boundary). Certain on-site performance is often unacceptable off-site. Hence, preventing or mitigating deleterious offsite effects is often the highest priority – especially contamination in the form of groundwater or surface water. While Nature cares little for administrative boundaries, such boundaries are useful locations to measure compliance with regulations. Boundary issues play an important role in most closure planning.

Boundaries are especially important if shared with another mine. Often several mines in a region share the same or adjacent orebodies and are slow to realize that they share responsibility for building the future landscape. Rivers need to be able to flow through this landscape that encompasses the efforts of one or more mines. There may also be implications for groundwater, wildlife, land uses, and any other fluxes that may cross the boundary. In some cases, there are opportunities at boundaries – especially in shared infrastructure, sharing of waste disposal sites, and regional planning.

Perhaps the greatest issue is the joint planning for acceptable landscape performance across the shared boundary, especially for ore recover and flow of lease-closure creeks and rivers. Such planning usually requires long term commitments to follow joint plans for landforms near the boundary. Decisions have to be made decades in advance, facing uncertainty in changing mine plans, and can potentially lead to restrictions costing mines tens of millions of dollars with possible sterilization of ore. There is clearly a need for mines to work closely together, sharing resources and technology, planning and risk by forging solutions that ensure good landscape performance – or risk solutions imposed by regulatory agencies. The oil sands region of Alberta is grappling with this regional challenge.

Reclamation costs

Given technical, planning, and regulatory uncertainties, especially if reclamation and closure occurs over several years or decades, reclamation costs can only be crudely estimated, perhaps only to within a half an order of magnitude for larger sites. Traditional reclamation usually costs $8,000 to $30,000 (Canadian) per hectare (largely depending upon the amount of resloping and coversoil thicknesses). Establishing a network of swales and creeks (the surface water drainage system) often adds 10 to 20 percent (or more if unplanned). Special costs related to remediation of specific issues, such as acid rock drainage or water treatment, can add tens of millions of dollars to the final cost at a particular site.

Typically, total reclamation and closure costs for a small mine are often in the $5 million to $15 million range. For larger mines, $30 million to $100 million is more common. For very large and complicated sites (especially those with several pits, problem water chemistry, and tailings impoundments), costs can be over $1 billion (for example, Syncrude and Wismut). Closure bonding costs (financial assurance for premature closure) can represent a significant fraction of the annual reclamation budget.

Gadsby (1996) pointed out that a well run mine site often has environmental costs (including reclamation) equivalent to one percent of its annual operating budget. Problem sites can reach as high as ten percent. Closure and reclamation costs, however, are not usually distributed evenly throughout a mine's life – even well run operations often incur 20 to 50 percent of these costs after closure which represents a cashflow and taxation challenge for most mines (Devenny, 1996).

Bonding for perpetual maintenance of say $1 million per year (not unusual for a site requiring water treatment), at a real risk-free rate of long term capital of three percent, may require $30 million of financial assurance– sometimes as much or more than the reclamation itself (e.g., Aziz and Ferguson, 2000; O'Riordan et al., 2001).

Annual research and development costs for some mine sites can be similar to those of progressive reclamation – some mines spend millions of dollars on reclamation research and development over their lifetimes. Closure planning costs, consultants' fees, and staff time in preparation of reports and designs, monitoring, and field supervision generally also run into the millions of dollars. These costs are not usually included in the total estimated reclamation costs.

Total reclamation and closure costs are difficult to estimate accurately and are especially difficult for most mines to manage at closure. While development of an industry database of actual costs incurred during successful reclamation would reduce some uncertainty, many mines are hesitant to divulge unit costs. Some regulators require bonding based on prescribed unit rates that are based on government contracts, often based on highway construction cost, which are usually much higher than mining costs.

Post-closure maintenance

At 30 of the mines visited, no consideration of long term maintenance has been given. Of the 27 that have considered maintenance, they are about equally split between planning for walk-away (maintenance-free) conditions, periodic maintenance (annual reviews, infrequent repairs as necessary), and active maintenance (involving scheduled maintenance or requiring a presence on site just about every day, for example to run a water treatment plant).

Most mining companies aim for a maintenance-free landscape though definitions vary widely and many are nonsensical (for example, when considering the term "maintenance-free" some miners confuse the goal of achieving continued landscape performance that is acceptable to stakeholders and regulators without ongoing intervention versus having a landscape that is simply free from maintenance). Miners at most modern metal mines expect some kind of long term maintenance. About a quarter of mines visited are aiming for varying degrees of periodic long term maintenance conditions to some extent and a quarter heading towards active perpetual maintenance. Some jurisdictions (e.g., Alberta) have refused to consider long term maintenance while others insist upon bonding for it.

Of the 12 mines visited that have plans for maintenance-free conditions, it seems likely only about half will continue to provide reasonable landscape performance without maintenance. Overall, it is estimated that only about a quarter of landscapes visited will provide good performance under a maintenance free condition whereas three-quarters will require some long term maintenance to achieve this goal. While this is clearly a subjective evaluation, at least some low level of ongoing periodic maintenance should be considered a common outcome.

Ideally, the landscape should be designed so that maintenance is only required for small areas, such as water treatment facilities, or is used as a secondary (rather than) primary line of defence against poor landscape performance. Too often, the entire landscape becomes maintenance intensive. Such broadly distributed maintenance activities may include removing trees from dump covers, pumping water between large ponds, replacing stream armour, road maintenance, annual dam safety inspections, and ongoing monitoring. Maintenance strategies in closure planning and landscape design are just starting to evolve – once it is recognized that some level of maintenance is likely, the landscapes can be designed with strategies that meet the needs of future owners.

2.5 Reclamation and closure goals – the theory

Despite a profusion of reclamation and closure goals expressed by miners, setting reclamation and closure goals is perhaps the most poorly managed aspect of closure planning. Clearly, goals are needed for minesite reclamation activity to guide design, budgeting, construction, and as a regulatory basis.

The covenant between the mining industry and society

Society allows mining because it decides that the value to society (the employment and mineral production) outweighs the sum of the relatively temporary disruptions and permanent changes to the landscape caused by mining.

Prior to mining, an environmental impact assessment is prepared and presented to regulators and stakeholders. Government regulators act on society's behalf, assessing or reviewing the anticipated effects of mining (economic, socio-economic, and environmental), deciding whether to permit the mine, and assigning and regulating conditions that the mine staff must meet during operation and at closure. The government also directly shares in more than half of the wealth generated by a mine through royalties and other taxes (Canadian Institute of Mining, 2001).

Along with regulations and subsequent approval conditions, this assessment and the subsequent approval is the primary source of reclamation goals and is part of a covenant between the mining company and society to reclaim the land to a useful state. This covenant is often referred to as mining's promise of "temporary use of the land" (Morrison, 2001). Failure to fulfil this covenant jeopardizes society's acceptance of the mining industry, and is partially responsible for today's anti-mining lobby.

Goals of a mining company and its directors

Directors are usually bound by codes of corporate governance that include compliance with applicable laws (OECD, 1999) and can be held personally liable for environmental compliance (Siemens, 1994). From a corporate perspective, reclamation is done for compliance and in the pursuit of profit. While there are ancillary benefits, reclamation is done because it is in the best interest of the mining company. While most reclamation specialists are generally focussed solely on technical goals and building good landscapes, their executives focus on cost, liability reduction, and environmental compliance. If compliance includes meeting agreed goals, then directors have a special interest in ensuring that the goals are structured so that compliance is practical and achievable.

2.6 Reclamation and closure goals – working poorly in practice

A compendium of goals

There is no shortage of imaginative goals for reclamation and closure. Some come from regulations and approvals, others from regulators, mine staff, stakeholders, and individuals. Table 2-2 presents a compendium of closure goals. Figure 2-4 summarizes the goals graphically. At most mines, there are only have a couple of stated goals and these were classified as primary goals. Most are usually vague or poorly defined. Most have numerous secondary goals, often chosen by the reclamation leader.

Just about all mine reclamation staff have a strong focus on creating stable landscape, greening it up with a vegetative cover, and meeting or exceeding reclamation and environmental regulations so that they can ultimately receive regulatory approval (and reclamation certification). There seems to be a strong and universal desire to make the land useful again. Return of the land to the state or crown and ongoing regulatory compliance were the most often mentioned goal on almost every tour.

Figure 2-5 provides a graphical representation of the top closure issue at each mine. Resolving this issue is usually the focus of reclamation and closure work. The top issue is split fairly evenly among five main categories: costs, vegetation performance, physical stability (geotechnical and erosional), acid rock drainage, and human safety (radiological, physical safety and building removal). At sites with ARD or radiological concerns, closure planning has a higher profile than at sites where safety concerns and offsite impacts are less prevalent.

Many of the secondary goals are pet projects of reclamation workers. Examples include rock piles for small mammals, enhancing game by providing winter feed, and research plots for their favourite vegetation species. Much of innovation in reclamation comes from these projects.

Land use goals present interesting challenges. Mine staff usually work with stakeholders and regulators to identify target end land uses that are often chosen to restore pre-disturbance uses. The targeted primary end land use (Figure 2-6) varies widely. About 40% of mines seek to provide natural or wildlife areas as primary land uses. About 30% aim for human uses such as agriculture, forestry, historic (preservation of mine workings as artefacts) and recreation. The remainder focus on simply providing a stable landscape for waste storage as a land use in itself.

Actual future land uses are beyond a mine's control – they are either at the discretion of the government land managers or may be inevitable (for example wildlife use, recreational use, future remining). This result has two important implications. First, target land uses themselves are design targets rather than goals. Second, if mines have ongoing liability for their reclaimed sites without control over their uses (and abuses), they will usually be unwilling to transfer custodianship of the site – this "custodial transfer barrier" is described later.

Mines that are more advanced in their closure plans usually recognize that the reduction in liability and approval and support of stakeholders and regulators are the overriding goals of mine reclamation and closure. Other goals are a means towards this end.

Exceeding regulatory goals

Almost all mining companies have a strategy to exceed regulatory requirements. This strategy recognizes that regulatory change generally lags behind technological advancement and experience, that exceeding regulations is a good strategy to avoid having regulatory decisions imposed upon the mine, and the desire to increase public support for the mining activities. However, ways in which the mine staff choose to exceed regulations are sporadic and sometimes counterproductive, especially when these include promises of unrealistic performance or land uses not favoured by stakeholders and regulators.

Going above and beyond the minimum requirements for reclamation can have public relations benefits which may be difficult to quantify but can be important to share value and long term viability of the mine. These efforts can be critically important when it comes time to renew permits or open new mines. Concern about policies that go beyond regulatory requirements is expressed by Henderson (2001). In many cases, mine staff have a better understanding of landscape performance, risk, and corporate liability than regulators and exceeding regulatory goals will be needed. Where goals are highly prescriptive (a common feature at US mines), most mines simply meet these minimum specifications, and good long term landscape performance is doubtful because the legislated requirements are insufficient, fail to take into account local conditions, and are often ill-suited to complex landscape systems.

Costly and high-risk goals

Costly and high-risk goals can arise at any time in a mine's life, but are most often offered or agreed to during the permitting process. Table 2-3 provides a list of high-risk goals that should generally be avoided because many cannot be met, are unreasonably expensive, or carry high levels of uncertainty. Most mining companies will have already agreed to more than one of these.

The temptation to agree to expensive goals is great because the (discounted) cost of meeting these goals at some future date may be less than the near-term cost of a permit delay. The result is a "permit at any cost" mentality. Often agreements are made by mine management without or against the recommendations of the reclamation specialists or and may reflect a poor technical understanding by negotiators. Eventually, mining companies typically argue that the cost of fulfilling these goals is unreasonable, and ask to be excused from them. Or worse, year after year goes by, with the staff promising to meet the goals at some unspecified time in the future. Agreeing to expensive mitigation measures is only ethical if there is reasonable assurance that the goals are technically feasible and that they are backed by the intent and resources to accomplish the goals in a reasonable time frame. Setting reasonable goals is a key area for improvement in mine reclamation and closure planning.

Evolving goals

Most jurisdictions reserve the right to apply new legislation to existing mines. Areas that are reclaimed (or sometimes all the areas that are disturbed) may be exempt from these changes, but this is seldom set out clearly. These jurisdictions also reserve the right to apply new legislation retroactively, even after the sites are reclaimed, certified, and returned to the state. Recent federal "polluter pays" legislation (Beaulieu, 2001) is an example of retroactive liability. It is therefore naïve to expect that closure goals will not change over time.

Britannia Mine is a recent example of retroactive liability (Judd, 2000; O'Riordan, 2001). The mine operated from 1904 to 1974 under numerous owners. Along with the present non-mining property owner, each previous owner has been named as a "responsible party" under the new Waste Management Act (Province of British Columbia, 2000) for cleanup of a century of acid rock drainage. Identified liability is up to $75 million and includes operation of a water treatment plant in perpetuity. It seems unlikely any of these operators expected to be liable for retroactive legislation.

Liability for unfulfilled goals

With unlimited time scales, no defined spatial scales for compliance measurements, and ever changing regulations, mines have unlimited liability for their activities and moving regulatory goal posts is one of their greatest concerns. Poor performance often invites stricter measures; good performance leads to higher expectations. Many mining companies believe they will discharge their liability upon reclamation; some recognize under existing provincial and federal law, they are liable forever. However, efforts have begun to find ways to restrict or allow transfer of liability under well-defined conditions (Beaulieu, 2001) to permit reuse of disturbed lands (e.g., Weber, 2001). For now, liability for mine sites remains a significant concern, especially for large mining companies with multiple operations, and also for small mines with limited capital resources.

2.7 Financial assurance

Requirement of financial assurance for reclamation started in the late 1960s and early 1970s. At that time, bonding was generally based on a modest cost of greening up the landscape and was usually offered in the form of corporate assurance (a pledging of assets), and negotiated during development of the mine, often amounting to a token amount of the final reclamation and closure costs. Effective financial assurance should be an ongoing requisite for any mining activity (Whitehorse Mining Initiative Environment Issue Group, 1994). Mining companies are being asked to provide financial assurance for the cost of reclamation and closure activities (in some instances for orderly shutdown, in other cases for instantaneous closure) and for any long term maintenance after closure.

Orderly vs instantaneous closure

More recently, mines are being asked to provide financial assurance for the instantaneous cost of closure. Many (perhaps most) mines close suddenly, and regulators want a pool of funds that can be used to reclaim the site if this happens. The instantaneous cost of closure for a large mine is often many times greater than the slow, progressive, considered reclamation and closure cost. For example, dumps can be capped with mine overburden at low or no cost since it has to be removed anyway – but this opportunity is only available if undertaken in a planned and orderly manner during operation. In some cases, there is no economic method to achieve closure goals if mining is halted prematurely – mines may continue to operate with annual losses to avoid going into the more expensive closure phase.

Instruments

Financial assurance often takes the form of cash, a letter of credit, bond, mining reclamation trust fund, corporate assurance, and sometimes a sinking fund or additional royalty per tonne (Solonyka, 2001).

When large financial assurances are required from start-up, this takes away capital (or makes it harder to raise capital), makes mining less profitable and, in some cases, prevents development of new mines. Levels of bonding may dominate project economics. Limiting the size of disturbance to that which can be bonded results in suboptimal mining scales.

Presently, bonding rates are negotiated with the regulators in most jurisdictions. Politicians may intervene, to direct regulators to require reduced rates of bonding or to accept corporate assurances instead of bonding in order to foster mining. Concerns for level playing fields and about political interference surface. Some areas are looking to legislate bonding formulas, mandatory means tests, and other less flexible methods (e.g., Ontario Ministry of Northern Development and Mines, 1999).

Insurance for mine reclamation liability is a new growth industry (e.g., Brodie Consulting Ltd, 1999).

2.8 Closure performance

Reclamation can be defined as the activities to restore the land to an agreed upon use and includes bulk regrading (and other ground preparation activities), placing coversoil, and revegetation. Decommissioning partially overlaps with reclamation and refers specifically to the final activities to prepare the land for certification and custodial transfer. It usually involves removal of improvements (buildings, pipelines, etc.), and finalizing the reclamation (fixing slumps, bare spots, armouring gullies, building rivers, etc.) Certification refers to the final inspection and approval of reclaimed and decommissioned land by government regulators. Custodial transfer is the formal transfer of the land to a new owner, usually back to the state.

At most mines, expensive and technically challenging reclamation activities are left until closure – part of a final decommissioning for the site. Many of the financial and technical challenges remain undiscovered until closure, leaving little or no time for research and innovation to offer solutions.

Reclamation activities during operation

As mentioned in the introduction, reclamation and closure planning occurs throughout the life of a mine. Progressive reclamation is that which occurs while a mine is still in its operational mode. All operating mines presently do progressive reclamation to one degree or another. Small to medium sized metal mines usually have only one or two waste rock dumps, one ore pit, and one tailings area which are all active at the same time — so only small peripheral areas can be reclaimed (typically 10 percent of the area disturbed). Larger mines reclaim dumps as they become available, but do not generally look for opportunities to accelerate reclamation. Reclamation is typically a significant annual activity only for soft rock mines (coal and oil sands) that produce land to be reclaimed at a steady rate.

Success varies by activity. Most mines have developed methods to economically and efficiently reclaim most areas. Bulk mine reclamation (regrading, coversoiling, revegetation) is reasonably advanced and economical, and miners are enjoying considerable success, at least in terms of preparing and revegetating large areas. Monitoring and maintenance of the landscapes during operation is usually lacking. Resloping of dumps and other reclamation opportunities are delayed in times of low commodity prices — a practice presently tolerated if the mine catches up in the times of higher profits.

Finer aspects such as fixing bare areas, establishing permanent creeks and lakes, water treatment for acid rock drainage, reclaiming roads or other infrastructure, or reclaiming soft tailings sites is generally not done during operation. The present framework of short-term economics and management's bonuses generally favours postponing reclamation and closure costs as long as practical during a mine's operation.

When a mine closes

While mine staff usually have the best intentions of completing their reclamation and closure activities soon after production ceases, many changes occur at closure, most of which are unforeseen yet follow a predictable pattern. Few mines are able to adjust to closure activities and sustain their efforts — most follow a less desirable path as described below.

Generally, there is a rapid reduction in the workforce at closure to 10% of its peak workforce. Then, after additional reclamation is complete, four to ten employees remain to finish or maintain the site, and later one or two caretakers are stationed permanently. The closure period is difficult for mine employees and contractors. Production usually ramps down in the latter years. Periodic suspension of operations (and layoffs) may occur when commodity prices dip. The most employable people leave. Most miners will experience at least one mine closure in their career.

As mines wind down, the local support for the mine rapidly evaporates (Neil et al., 1992). No longer able to support the local economy, the mining company's negotiating position with townspeople and regulators is greatly diminished and relationships usually become antagonistic.

Closure usually happens suddenly, often due to a major accident or due to a sudden commodity price drop. People move away, house values drop, and businesses go broke (Neil et al., 1992). The community suffers a "de-multiplier" effect as the highest-paid portion of its population moves away. If the town is small, economic collapse ensues. If the town escapes collapse, it will usually require years of government assistance to adjust to its new conditions. There is a growing literature (e.g., Kunanayagam et al., 2000) on sustaining mine towns after mine closures, but many of the schemes are expensive for the mines and governments and are ultimately not sustainable.

At many mines, only the people with the most seniority remain after closure. For a few years prior to retirement, a mine manager takes care of the bills, reports to the home office and the government, and tours visitors. One or two other senior tradespeople take care of the electricity, pumping water, digging ditches, and maintaining the site. Water treatment permanently employs four to ten people who also do other maintenance at the site.

Mine closure is also usually a difficult time for reclamation and closure activities at all mines. The sudden shutdown of the mine and the immediate layoffs means that a tremendous amount of information and site experience is lost. The filing systems at mines are often poor and information is often thrown away as offices are shut down and buildings demolished. This loss of information and experience can be referred to as the "closure information gap." There is often a major change to the closure plan at this time. Big equipment that was to be used for closure activities is sold or moved to a nearby mine. Cash flow ceases, the warehouse and local shops close, and those who kept the mine running smoothly are gone.

There is a large area left to be reclaimed, usually 50 to 80 percent of the site. Expensive ground preparation activities remain to be done before traditional reclamation activities can take place, and the task can be daunting (e.g., McKenna, 1999). The mine is no longer profitable so expenses can no longer be written off against profits or royalties and the mine pays the full amount of these activities which can effective doubles costs (Dave Devenny, 1999).

In most cases, closure activities and reclamation activities are simply halted, and the site goes into dormancy. Pumping stations and pipelines are set up to move water around the site, often to fill the abandoned pit. Buildings and shops are demolished. Mining equipment is mothballed or more commonly simply parked. Disused powerlines drape the landscape and "No trespassing" signs are posted as the access is barricaded. Token reclamation tasks may be done to satisfy regulators that some progress is being made. This reclamation often starts with the easiest work or work such as dump capping to minimize ongoing water treatment costs. Of the quarter of the mines visited that had recently closed, half were in a state of reclaimed dormancy, the rest in partially reclaimed dormancy.

Stated reasons for dormancy include:

- selling or reopening of the property
- still developing and negotiating closure plans for the sites
- too busy reclaiming and closing other sites
- extending closure activities over years based on discount cash flow economics
- hoping for or developing a new technology to reduce closure costs
- hoping for a regulatory change in heart (or personnel) which will allow it to do less reclamation than expected
- feeling that the benefits of reclamation do not justify the high costs
- simply wanting to avoid reclamation costs.

The certification barrier

Despite reclamation at 51 of 69 mines which totalled nearly 21,000 hectares (the size of a prairie city), only two of the mines had any land certified and none had returned custodial transfer of any land back to the state.

One of the main reasons to apply for reclamation certification is reduction of liability for the land and the main goal of just about every mine is to return the land to the state. The lack of land being certified is a critical failure – the ultimate goal of reclamation is not being achieved. Not only is it a failure of the mine, but also of the regulators whose job is to ensure acceptable reclamation and return of the land. And the industry is failing to meet its covenant of "temporary use of the land." Today, with few exceptions, mining is still a final land use – once the mine is finished with the land, it hangs onto it indefinitely.

The lack of certified land points to a "certification barrier." Based on observations and interviews at the mines visited, there are numerous reasons for this barrier:

- the goals for the landscape are poorly defined – it is unclear if the landscape is meeting and these goals
- there is considerable uncertainty regarding long term landscape performance
- avoiding certification avoids raising the thorny issue of long term maintenance
- once certified, the land becomes off-limits to mine infrastructure
- there is little incentive for the mine to give up control of the land and even less for the state to take control
- liability for the certified land is uncertain – the mine gains little through certification while the regulator is usually unwilling to accept the liability.

Mines are hesitant to fail in their efforts to certify land because it could have some dramatic effects:

- embarrassment for the mining company
- a risk of re-evaluation of liability for the rest of the site (which may trigger a review of bonding levels or methods, or re-opening of the environmental impact assessment)
- shareholder value may decrease
- management's bonuses may be affected
- in most cases, a reclamation order must be issued with specific time limits. If the mine fulfils its order, the land must be certified. While it remains unfulfilled, mines may have

difficulty (or it may be legally impossible) to get extensions of operating licenses, expansion permits, or in some cases, start any new mining activities elsewhere in the country.

Mines and regulators dwell on these issues and almost no land is certified. On the other hand, there is incentive for the mine to progressively certify the land:

- progressive reclamation combined with progressive certification is a part of sustainable development (Mikalson, 1995)
- some liability for the land is transferred to the state
- it assures that all reclamation work is complete and reclamation practices are acceptable
- harder for "moving goalpost" regulations to affect certified land
- it forces many of the issues of acceptable landscape performance and successful reclamation and establishes precedent
- financial assurance can be released
- the certification activity can be budgeted, staffed and tracked as a normal function of the reclamation department
- certification the ethical conclusion to the promise of "temporary use of the land"

A success story

Transalta's coal mining operations near Edmonton are the only mines visited that have progressive certification (see Mikalson, 1995). Every year, about one hundred hectares are disturbed, another hundred reclaimed, and another hundred certified. This process provides yearly progress and demonstration of sustainable development. There is a permanent staff position that co-ordinates the paperwork and applications. Certification is fully integrated with the day-to-day operation (Bateman, 2002) and forms a model for the rest of the mining community. The mining company has earned a high level of trust between regulators and stakeholders. For mining to enjoy successful reclamation, this process has to start at all mines.

The reader may be familiar with other success stories, where mining companies and regulatory agencies are achieving greater success than those visited in the present study. And as described above, most mines have some successful aspects of their reclamation and closure planning programs. Such experience should be documented and shared widely to provide examples and models for the mining companies and regulatory jurisdictions that are struggling – the situation for the mines visited in this survey.

Custodial transfer barrier and the liability trap

Most mining companies recognize that they are liable for the sites forever. Reclaimed landscapes are often fragile – re-mining, logging, or other disturbances to the site may trigger poor landscape performance (especially erosion) that may require repair. Miners are unwilling to give up sites for which they are liable to unknown third parties or to the state – this is the "liability trap." Good corporate governance may preclude relinquishing control of land for which the mine is liable.

Mines are especially unwilling to give up control of the sites if there is long term maintenance of the site required – damage by other users could increase maintenance costs. Vandalism remains a common problem (for at least half the mines visited) so mining companies control access to the site.

A new ideal

Closure, though inevitable, is a difficult time in the life of any mine. A staged, orderly successful closure should evolve over years of closure planning and progressive reclamation, culminating in a planned shutdown of ore production and milling, with more and more people and resources being assigned to final reclamation and closure activities. There would be no surprises, and within a few years, the last area would be certified and the control and liability of the fully reclaimed minesite would be transferred to a willing custodian.

To achieve this new ideal, a more formal process of setting realistic goals is needed, and engineering tools applied to achieving these goals through better design, construction, operation, monitoring, and maintenance. Closer integration of closure planning with operations and better oversight of progress towards closure goals is needed. A stronger emphasis on return of land to the state is needed by both the mining industry and its regulators, and to this end, changes to provincial and federal liability laws are needed.

2.9 Summary and conclusions

Sixty-nine mines were visited to determine the status of closure planning and to learn about typical activities at closure (closure performance). It was found that though most active mines are doing closure planning, efforts are not well integrated with or significantly influencing operational activities except for directing long term research.

Of particular concern is the goal setting process. Goals are poorly defined, often complex, and usually unachievable. Miners often follow a "permit at any cost" and promote or agree to unreasonable and unachievable goals. Reclamation goals usually exceed those required by regulators, but are seldom realized.

Both a certification trap and a liability trap exist. Almost no mining companies are certifying land for fear of being turned down and none are giving up control of the reclaimed landscape to the state due to ongoing (and unlimited) liability for the site. At closure, planned reclamation activities usually slow dramatically, knowledgeable staff leave, and a closure information gap occurs. Activities at the mine site stops short of full reclaimed, and the sites are being held in long term dormancy. In short, the mining industry is not fulfilling its social covenant of "temporary use of the land."

Several items need to change: miners need to only agree to reasonable, simple, and achievable goals, then set about achieving these goals reliably. A more formal system of landscape design to ensure good long term landscape performance is needed. Miners need to integrate their closure planning process more closely with operations to be able to achieve these goals. Regulators need to require progressive certification and legislators need to create methods that ensure reasonable and achievable transfer of liability for properly reclaimed sites.

Emerging is a concept of successful reclamation – reclamation that supports the mine's activities, meets agreed upon goals, includes progressive certification and transfer of liability, and can be reasonably assured of providing good long term landscape performance.

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Table 2-1 The breadth of mines visited

Aspect	Mini-mum	Typical	Maximum	Comment
Total production (tonnes per day (ore and waste))	10	10,000 – 30,000 for small mines 100,000-200,000 for large mines	~1,000,000	In terms of annual ore production, Canadian mines visited accounted for half the open-pit production, one-third the underground production, and all the oil sand production. The fifty Canadian mines visited represent about 20% of the 277 Canadian mines presently in production.
Peak workforce	27	200-500 for small mines 800-1800 for larger mines	7000	These numbers decline in latter years, and at closure, all but 10% of peak workforce remain. Dormant sites typically have 2-4 people.
Disturbed area, ha	1	10-100 for small mines 1000-3000 for large mines	15,000	A recurring theme was an open-pit metal mine with a waste rock dump and a tailings pond each equal in area to the mined-out pit and totalling about 500 to 1000 hectares. About 10% of land disturbed by Canadian mining was visited. Areas that are less than about 100 hectares are relatively less complex to reclaim.
Reclamation rate, ha/yr	0	20-50	300	Few mines have steady annual reclamation rates – most have blocks of land that become available periodically or at closure.
Percent of disturbed area reclaimed	0	10	100	Closed mines often reach 80-95% of the disturbed area reclaimed. Operating mines (especially metal mines) typically have 10-20% of their area reclaimed.
Coversoil thickness, cm	0	30-100	300	Thicknesses often determined more through economics and availability than land-use requirements.
Mine opening date	1900	1950-1980	2000	
Mine closure date	1905	1980-2010	2100	
Age, years	3	30-60	100	
Elevation, masl	50	1000-5000	6300	
Precipitation, mm/yr	160	300-700	2000	Few mines consider climate in their reclamation other than in choosing vegetation.

Other statistics	
Main commodity	Gold/silver (3), copper (8), nickel (2), uranium (12), coal (24), oil sands (8), industrial minerals (6), other (3)
Mining method	Open pit (9 quarry, 15 metal, 13 coal, 8 oil sands), underground (18 metal, 7 coal) other (3)
Mine status	Active (23), closure (10), care and maintenance (7), dormancy (6), abandoned (8), historic (5), renewed reclamation (10)
Region	BC Coast (4), BC Interior (12), Canadian Rocky Mountains (11), Prairie (9), Oil Sands (9), Northern Ontario (9), Colorado Plateau (12), Germany (3)
Regulatory jurisdiction	British Columbia (20), Alberta (24), Ontario (9), Colorado (1), Utah (5), New Mexico (6), Ohio (1), Germany (3).

Having certain landforms / conditions	Dumps (48), underground workings (22), end pit lakes (26), highwalls (29), soft tailings (17), tailings beaches (19), tailings slopes (19), acid rock drainage (20)
Closure planning status	No reclamation (2), no plan (23), simple reclamation plan (13), full closure plan (31)
Unanticipated concerns (surprises during operation)	Acid rock drainage (15), metals (5), uranium (11), selenium (5), spontaneous combustion (4), erosion (3), liquefaction potential (4), soft tailings (6)

Table 2-2 A compendium of closure goals

Financial

- Avoid impacting other company mines by having a violation
- Bond release
- Bond roll over
- Create maintenance-free landscape
- Future re-mining
- Have same closure goals as sister mine nearby
- Keep mine open for future mining (no cover reclamation)
- Keep minesite in dormant state
- Minimize closure costs
- Minimize monitoring and maintenance timeframe
- Minimize post-closure monitoring costs and monitoring time period
- Public relations for mining company, government, stakeholders
- Recapitalizing next economy
- Reduce liability
- Reduce long term maintenance costs
- Return of land to original landowner
- Satisfy stakeholders
- Sell buildings and equipment
- Store water for as long as possible
- To reduce levels (flux) of ARD required for treatment
- Tourism
- Walk away (run away) unreclaimed
- Zero liability

Cultural

- Aesthetics
- Avoid disturbing archaeological sites in the first place
- Avoid hard erosion control measures
- Avoid sabotage
- Avoid vandalism
- Build good will among stakeholders and regulators
- Don't restrict livestock wildlife with fences
- Employment/jobs/construction company/spending others money
- Historical preservation
- Involve the community in research and reclamation
- Limit vehicular and other unauthorised access (trespassing)
- Remove scrap and trash
- Retribution
- Road reclamation
- Satisfy local residents
- Visual similarity

Regulatory

- Avoid declination or certificate
- Avoid use of non-natural materials
- Cover mine waste
- Don't be too complicated
- Meet soil capability guidelines
- Meet vegetation requirements, especially percent cover
- Meet water quality (on site and off site)
- Minimize solids loading and offsite erosion /deposition criteria
- No subsidence
- Pork-barrelling (make work projects)
- Regulatory approval/compliance
- To remove any contaminants from the site
- Uniform slopes with no gullies, potholes or depressions
- While in its dormant state, have it meet environmental regulations

Physical

- Avoid aeolian erosion
- Avoid animal induced erosion
- Avoid off-site seepage contamination
- Avoid river erosion
- Avoid seismic damage
- Avoid spontaneous combustion of (coal) spoils
- Cleanup and removal of infrastructure
- Cover bad materials
- Geotechnical stability
- Have little erosion and no off-site erosion.
- Low risk to human health
- Maintain water cap
- Removal of physical hazards
- Restore aquifers
- Use micro- and meso-topography to control erosion and add diversity

Land-use

- Chose land uses that are the cheapest to create
- Commercial forestry
- Create a hydroelectric facility
- Create a mix of land uses
- Create aquaculture
- Create farmland
- Create fish habitat
- Create gardens or spas
- Create grasslands
- Create industrial park
- Create landfills
- Create natural area
- Create park
- Create ranchland
- Create wildlife habitat
- Recreation
- Return land to original land use
- Return of original land use
- Traditional land use

Biological

- Creation of wetlands
- Edge effects for wildlife
- Equivalent land capability
- Good as or better than mining or better than before revegetation
- Green up historic mining areas
- Green up the site
- Kick-start the natural successional process
- Meet a bioproductivity level
- Meet soil chemistry requirements
- Mimic reference area
- Not to provide coyotes habitat
- Planting diversity
- Promote rare wildlife (bats) or exotic wildlife
- Provide diversity of slopes and veg
- Restore damaged offsite lakes
- Restore native vegetation (non-exotic)
- Rocks for rodents
- Soil conservation
- Sustainability
- Water for cows

Chemical

- Store water
- Water discharge without treatment

Other

- Able to drive a truck over it
- Create test areas
- Just be stable
- Manage water infiltration and runoff
- Meet personal needs
- Meet professional requirements
- Mimic natural conditions
- Return spirituality to land
- Stop human habitation
- To create long term employment

Table 2-3 Examples of unrealistic or high-risk goals

Type of unrealistic or high risk goal	Examples
Promises that go against nature	• planting exotic trees in the desert • creating self-sustaining oasis in desert • no erosion on planar slopes • wildlife can be kept from feeding on metaliferous vegetation
Promises with no definition	• create rich biodiversity in final landscape where biodiversity is not defined • make the land better than it was before
Promises based on development of future technology	• agreeing to plant rare species that have never been planted • agreeing to develop or breed species are tolerant to elevated salts or metals • agreeing to use only native species for all areas of landscape • agreeing to develop new computer models for prediction • agreeing to develop new (or less costly) water treatment system • agreeing to develop new tailings disposal methods
Promises with low probability of success	• a promise to create a maintenance-free landscape in tough acid rock drainage conditions where everything would have to go perfectly for success • use of passive wetlands for bioremediation of metals • avoid release from water treatment areas during extreme precipitation events
Promises that are technically impossible	• the site will have no erosion • no subsidence of a compressible fill will occur • restoration of original contours everywhere • meeting dozens of promises simultaneously • no erosion of fills placed on floodplain
Promises based on complex numerical models	• complex computer models that show certain end-pit lake performance far into the future under all conditions • ecological succession models to show future growth and ecosystem development • achieving certain habitat suitability indices for wildlife
Promises with-open ended timeframes and promises that cannot be tested in human time-scales	• perfect performance in perpetuity • zero probability of any geotechnical instability • promises of good performance in the probable maximum precipitation event (PMP) or probably maximum flood (PMF) • no unwanted groundwater contamination for 10,000 years • perfect performance of internal filters and pipes in tailings dam
Promises that are not self-sustaining or ignore natural ecological succession	• using grassy patches for wildlife in a dense forest • creation of specific ecosystems at odds with soils or aspects
Promises with that ignore economic reality	• backfilling of all mined-out pits after closure • use assets at closure to pay for remaining reclamation • maintain post-closure levels of employment present during mining • zero liability at a complex minesite • estimation of liability with precision • clean up of all wastes to background levels
Promises that ignore human nature	• have no damage from trespassers on fragile sites • keeping fish from lakes and streams
Promises that may be conflicting	• commercial forest and traditional land use • recreation and wildlife • natural species and intensive agriculture • full remediation and historic preservation • perfect ongoing performance and maintenance free • original contours (with new materials) and erosion free • aesthetics versus landform stability • logging of tailings sand slopes and erosional stability

Figure 2-1 Map view of mine site locations visited

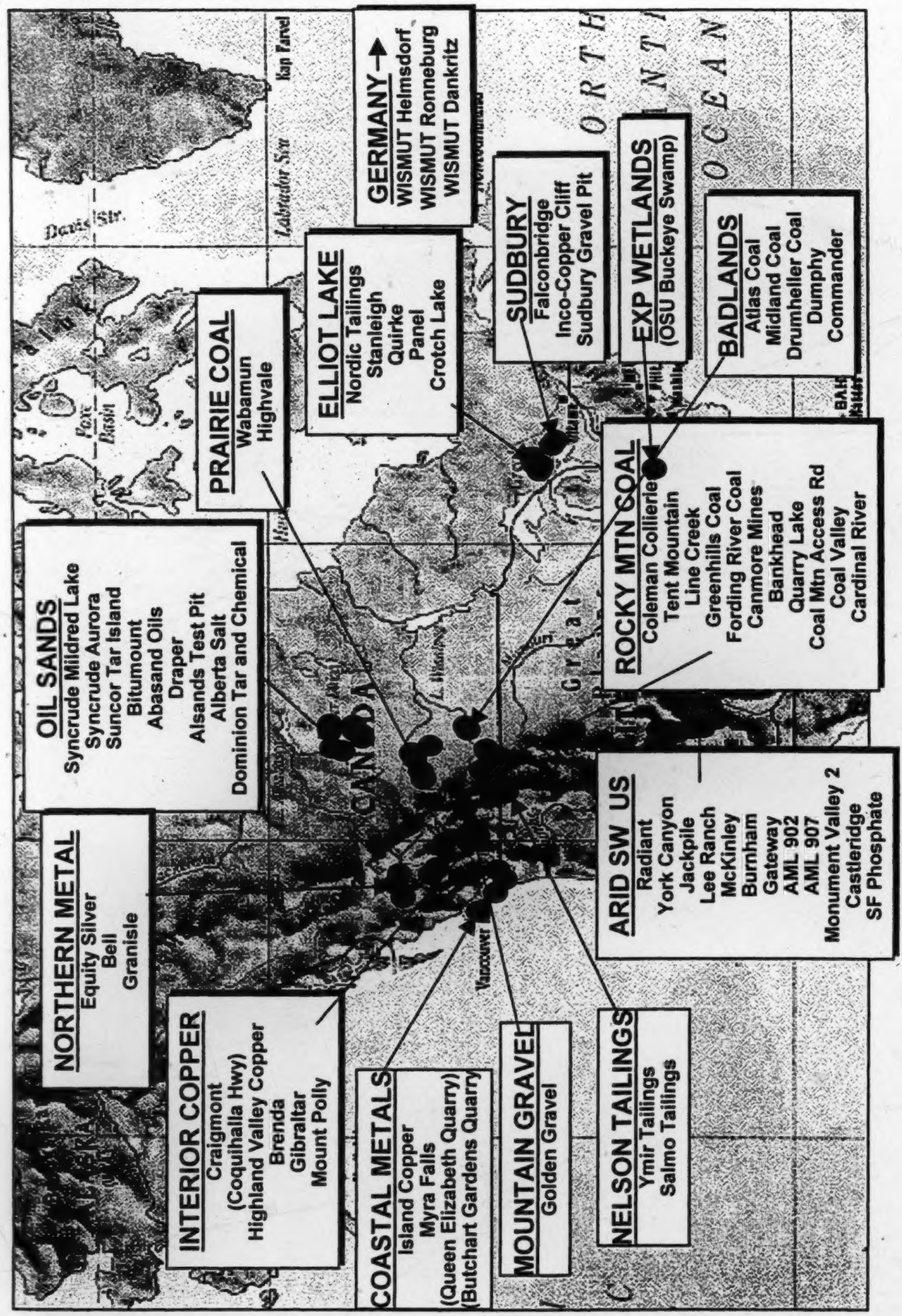

INTERIOR COPPER
Craigmont
(Coquihalla Hwy)
Highland Valley Copper
Brenda
Gibraltar
Mount Polly
NORTHERN METAL
Equity Silver
Bell
Granisle
OIL SANDS
Syncrude Mildred Lake
Syncrude Aurora
Suncor Tar Island
Bitumount
Abasand Oils
Draper
Alsands Test Pit
Alberta Salt
Dominion Tar and Chemical
PRAIRIE COAL
Wabamun
Highvale
ELLIOT LAKE
Nordic Tailings
Stanleigh
Quirke
Panel
Crotch Lake
GERMANY→
WISMUT Helmsdorf
WISMUT Ronneburg
WISMUT Dankritz
SUDBURY
Falconbridge
Inco-Copper Cliff
Sudbury Gravel Pit
EXP WETLANDS
(OSU Buckeye Swamp)
BADLANDS
Atlas Coal
Midland Coal
Drumheller Coal
Dumphy
Commander
ROCKY MTN COAL
Coleman Collierie
Tent Mountain
Line Creek
Greenhills Coal
Fording River Coal
Canmore Mines
Bankhead
Quarry Lake
Coal Mtn Access Rd
Coal Valley
Cardinal River
ARID SW US
Radiant
York Canyon
Jackpile
Lee Ranch
McKinley
Burnham
Gateway
AML 902
AML 907
Monument Valley 2
Castleridge
SF Phosphate
COASTAL METALS
Island Copper
Myra Falls
(Queen Elizabeth Quarry)
(Butchart Gardens Quarry
MOUNTAIN GRAVEL
Golden Gravel
NELSON TAILINGS
Ymir Tailings
Salmo Tailings
Vancouver
Davis Str.
Labrador Sea
Kap Farvel
Foxe Basin
CANADA
Great
NORTH
ATLANTIC
OCEAN

Figure 2-2 Disturbed and reclaimed areas of mines visited

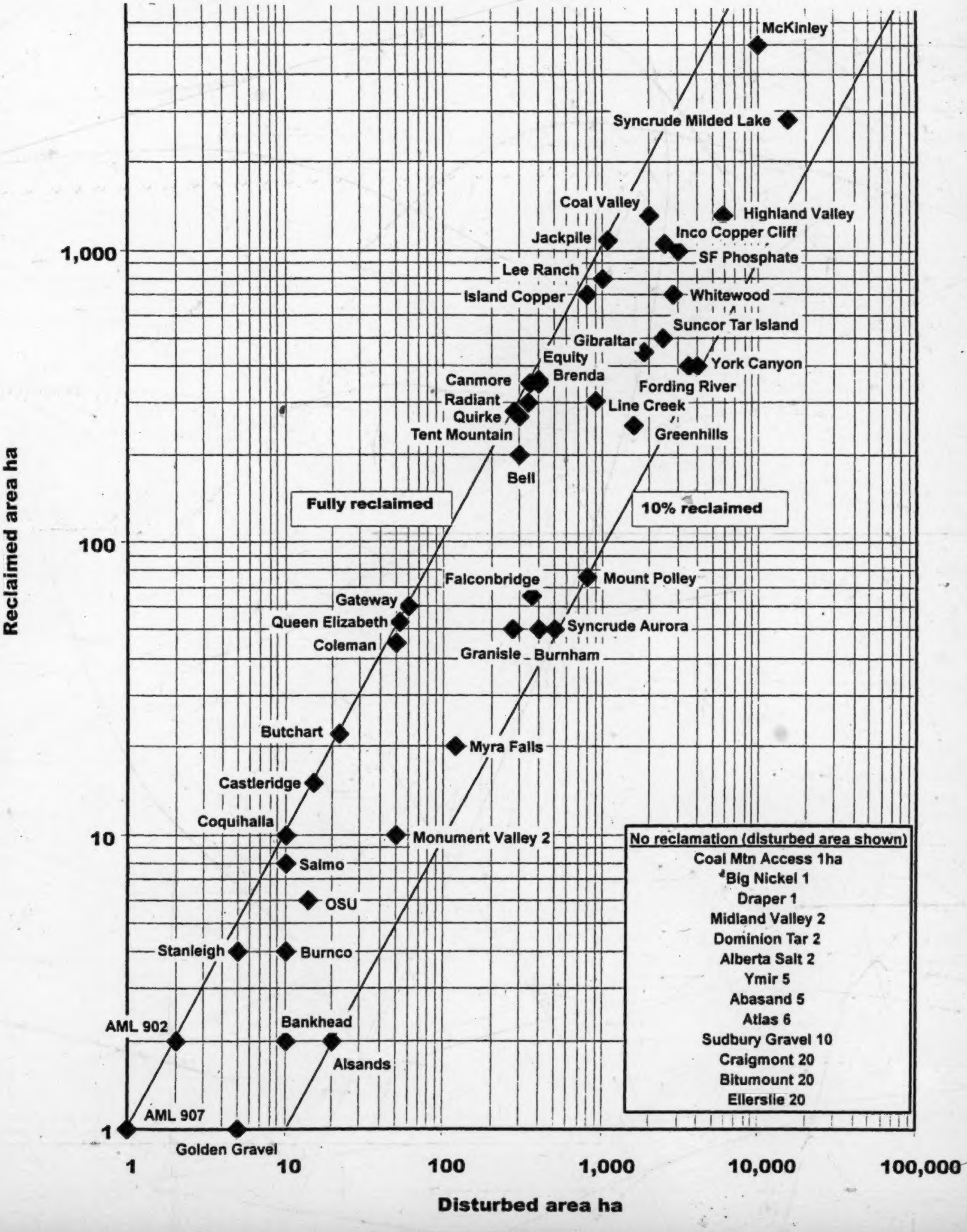


Figure 2-3 Reclamation and closure planning status

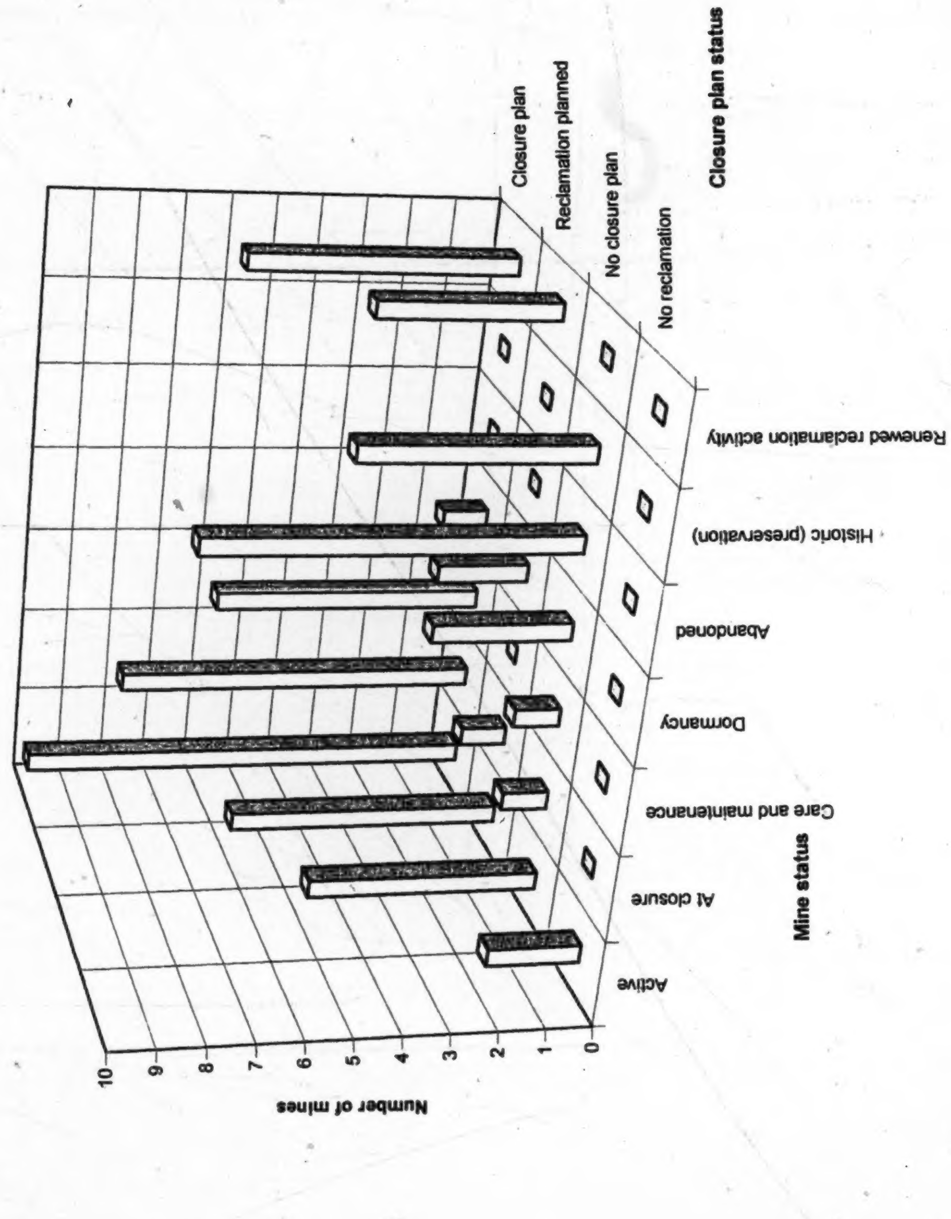


Figure 2-4 Primary and secondary goals

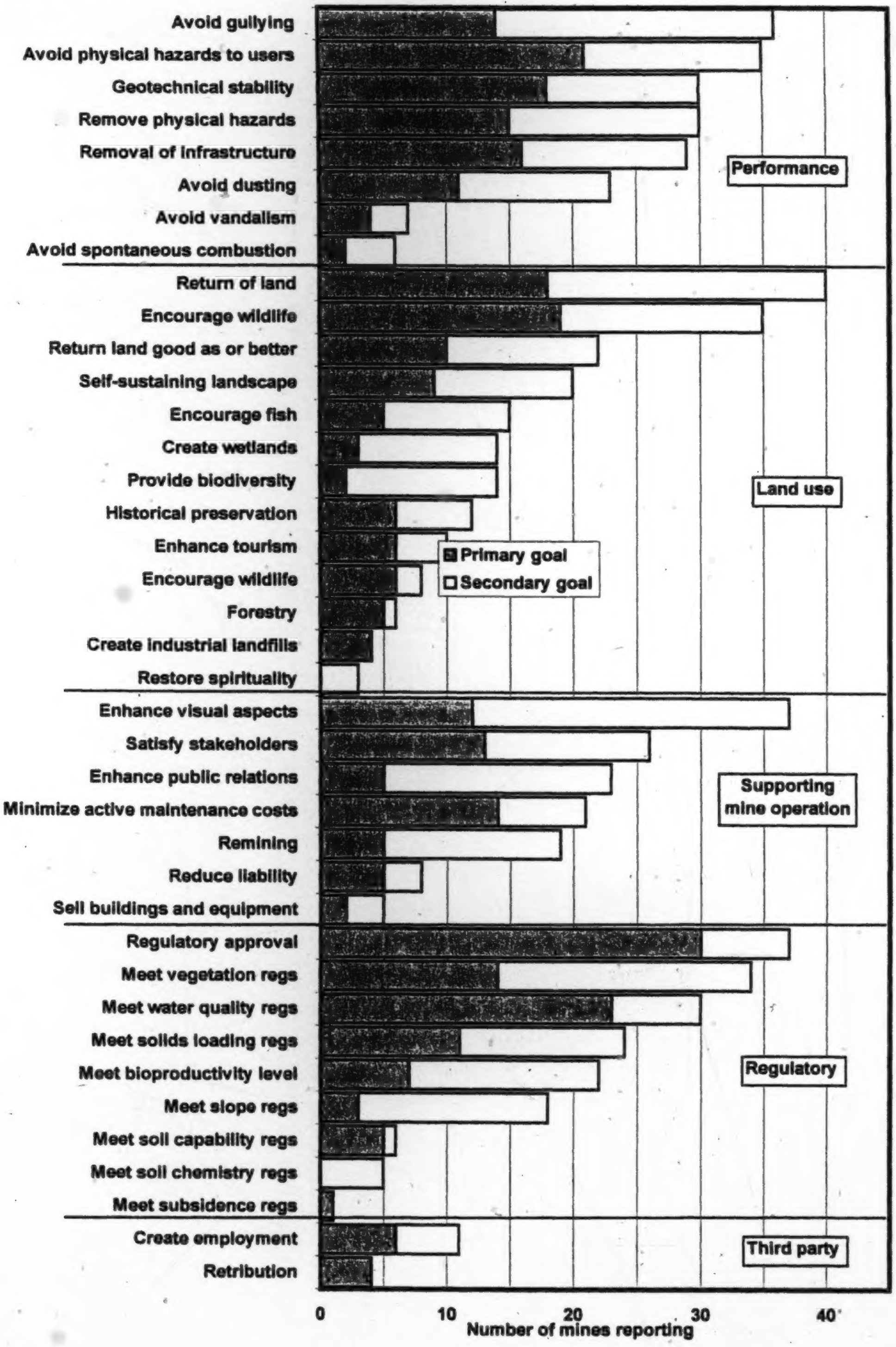


Figure 2-5 Number one closure issues

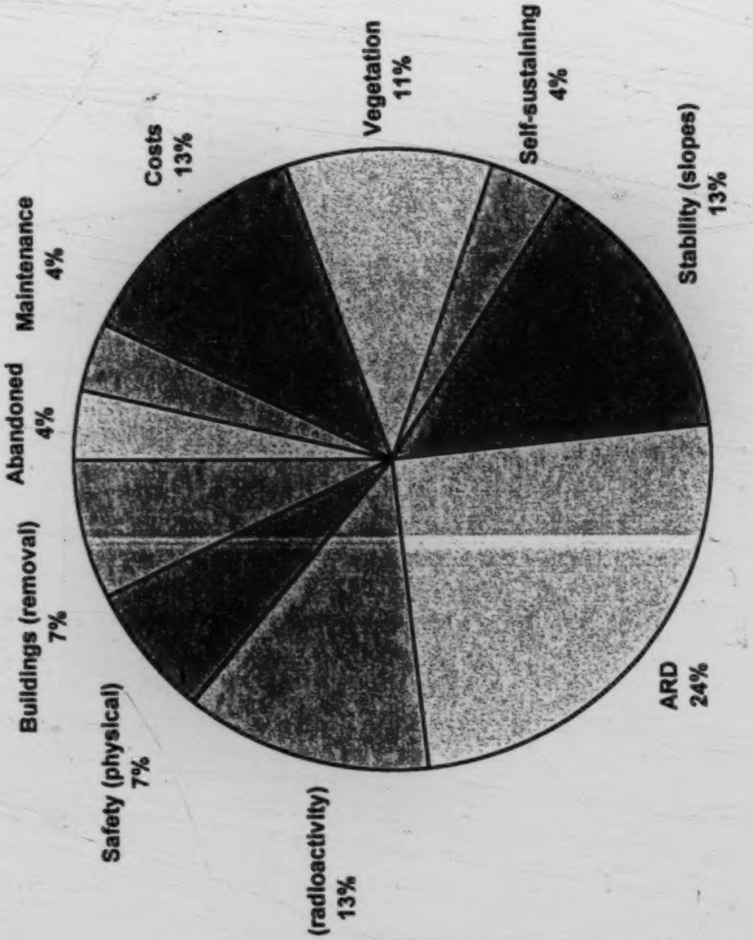
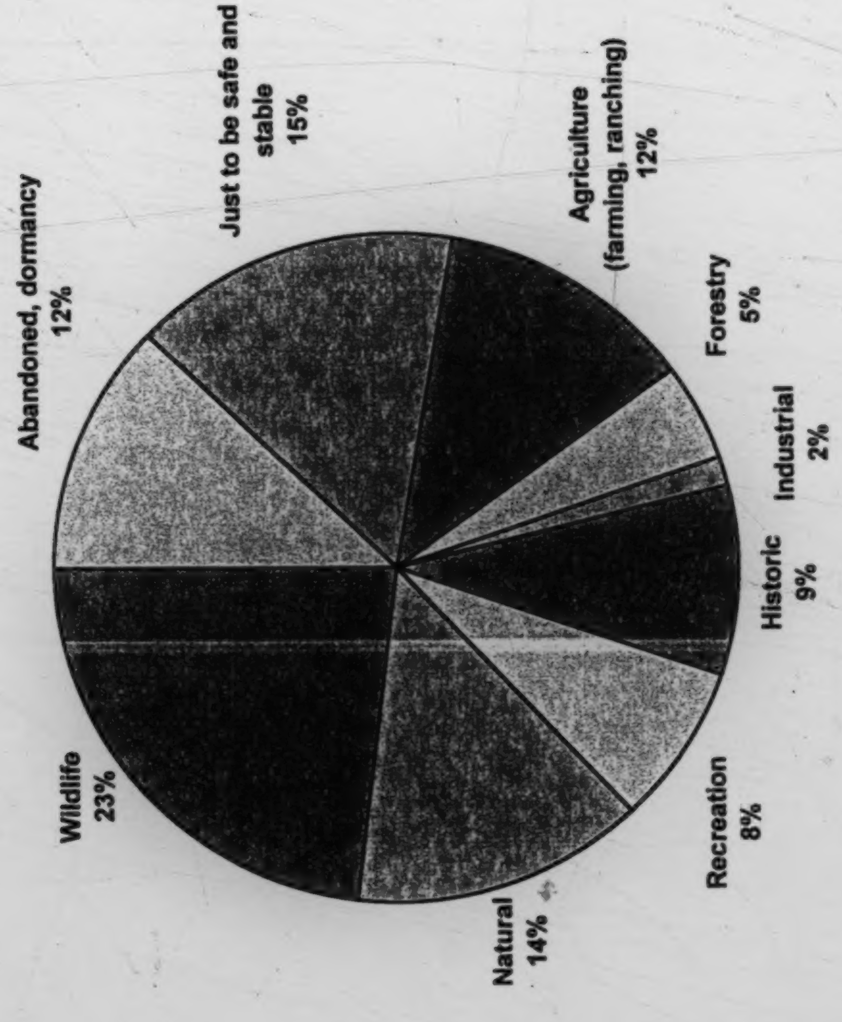


Figure 2-6 Targeted primary end land use



Chapter 3

Observations on landscape design and performance

3.1 Introduction

Successful reclamation of mined land, requires, among other things, a landscape design process and acceptable landscape performance. Landscape design is the collection of activities that go into the design of mining landforms and landscapes and includes investigation, analysis, planning, drafting, and field design. Landscape performance is the present behaviour of the landscape and individual landforms, especially as measured against agreed upon goals and includes the reliability of continuing to meet these goals well into the future. For most mine reclamation, good landscape performance includes being geotechnically stable with acceptable erosion rates and offsite impacts, a thriving ecosystem, an environment safe for humans and animals, and the capability to support desired land uses.

To learn the state of practice in landscape design and observe landscape performance, 69 minesites in Canada and the United States were visited. This chapter outlines the study methods, surveys the literature, and summarizes the current state of practice for landscape design. It describes reclaimed landscape performance based on various mining terrain units then at the landscape level. Scorecards are presented. The chapter concludes with a discussion on meeting landscape performance goals reliably and the need for a more formal, integrated approach.

3.2 Methodology

Sixty-nine minesites were visited between 1996 and 2001 as described in Chapter 2 and Appendix A. Several hours were spent at each mine, observing performance of the reclaimed areas – a visual inspection of geotechnical and erosional stability, lushness of vegetative covers, effects of seepage water, signs of wildlife, and integration of reclamation with the mining operation. Many of the insights came from frank discussions with reclamation leaders to learn what strategies and techniques were working, and what were not, what surprises had been encountered, and how likely the landscape was to meet the agreed upon performance goals. Opinions expressed by reclamation staff at the mines were in general agreement with visual observations made by the author, and also generally consistent with opinions expressed by regulators and consultants involved with the mines.

It is useful to evaluate reclaimed landscapes by discipline and at two spatial levels, the terrain unit level and the landscape level. Most mining landforms (e.g., waste dumps, tailings ponds, pits) are composed of several anthropogenic terrain units (e.g., plateaus, beaches, slopes). A landscape, broadly speaking, is all the land (and water) that can be seen from a vantagepoint, and refers to the whole mining disturbance area and the surrounding adjacent land.

3.3 Literature review

The literature on specific elements of design is vast but on integrated design for mine reclamation, it is sparse. Technical papers that deal with broadly with landscape design include those by Adams (1983), North Dakota State University Land Reclamation Research Center et al. (1983), Australian Mining Industry Council (1987), Harwood and Thames (1988), Brown et al. (1992); Barton (1994); McKenna and Dawson (1997); Achari and Hettiaratchi (2001).

Papers that relate to key disciplines include mine waste geotechnics (Daniel, 1993; Dawson, 1994), seepage and drainage (Harr, 1962), reclamation soils (Hu, 1997; Haigh, 2000), vegetation (Hutnik and Davis, 1973; Newey and Lewis, 1976; Wollenhaupt and Richardson, 1982; Hu, 1997; Leavitt et al., 2000; Sanak-Oberndorfer et al., 2000; Gerbrandt and Sawyer, 2000), and wildlife (Green et al., 1986).

The mine reclamation literature is vast, much of which focuses on soils and revegetation. Proceedings from reclamation symposia, such as the British Columbia Mine Reclamation Symposia, the Canadian Land Reclamation Association Symposia, and the Billings Land Reclamation Symposium provide a wealth of information.

Disciplines that relate to landscape design include: ecological engineering (Yan et al., 1993; Mitsch et al., 1993), value landscape engineering (Liljegren, 1994), and planetary engineering (Huyghe, 2000).

3.4 Landscape design and construction (by technical specialty)

This section looks at the various technical specialties that need to be involved in generating landscape design. Tables 3-1 and 3-2 provide a summary and scorecard.

Geotechnical

Most geotechnical aspects of mining landforms are usually well handled, mainly because formal geotechnical design of dumps and dams is required by regulators — an outcome of the 1966 Aberfan disaster (Bishop, 1973).

Most of the sites visited have good slope stability. Some have a few small slumps that do not impact overall landscape performance and these are limited in size and number. Some slopes may be at risk to long term instability due to unanticipated toe erosion, rising water tables, or seismicity. It is usually implicitly assumed that end-of-construction stability governs the design – long term stability is seldom evaluated. Ten percent of the minesites had some slope instability; but in many cases, the instability was relatively minor.

Subsidence, especially differential subsidence, is characteristic of thick fills such as dumps, and soft tailings. The two greatest impacts are for structures founded on these substrates (including buildings, roads, pipelines, powerlines, ditches, and covers) and for shallow ponding of water. Other than changing soil moisture conditions, subsidence was not seen to be great or contributing to degraded landscape performance at most sites. However, subsidence deserves greater consideration in design because of its effects on surface-water hydrology and soil moisture regimes.

Stabilization against cave-ins from undermining is common practice in underground coal mining in urban areas. At the sites visited, concrete plugs and grouting of near-surface voids seem to be straightforward (though costly) and while the performance of the plugs is good, long term concerns regarding cave-ins or subsidence in grouted areas usually require long term financial assurance or insurance. The literature has many examples of undermining disaster sites (Johnson and Miller, 1979) and undermining cases were under-represented in this survey (Alberta underground coalmines and German uranium mines were the only sites visited experiencing concerns).

Dam safety is a long term issue at many mines. Recognition of the need for long term monitoring of tailings facilities comes as a surprise to many mines. Recent changes to Canadian dam safety guidelines (Canadian Dam Association, 1999) do not fully recognize the unique nature of long term tailings dams, particularly those that have no water reservoirs but contain potentially mobile materials. Many sites are presently heading into long term instrumentation monitoring, annual inspections and report, emergency preparedness plans, five-year audits, and other activities related to dam safety.

Soft tailings stabilization is a costly geotechnical issue described later.

Methods by which landforms are designed, constructed, licensed, and monitored to meet geotechnical goals, and the requisite care and effort that goes into these endeavours can serve as a model for other specialities involved in landscape design.

Surface-water hydrology and topography

Hydrology is perhaps the most significant issue for mine reclamation across North America. The reasons for its importance are that it is fundamental to the physical stability of the landscape (upon which the soils and vegetation and ultimately end land use depends), it is a mechanism for unravelling of the rest of the landscape, and flowing water is one of the major vehicles for causing significant off-site impacts.

Re-establishing the surface-water hydrology is a major issue for mines and often costs between 10 and 20 percent of the total reclamation and closure costs. Almost half the sites visited had no formal design for slope drainage or creeks/rivers. At a quarter of the mines, streams are “semi-designed” – field fitting without engineering. Most streams are only designed for 100 to 200 year events with no consideration for exceedence. Potential blockage (from beaver dams, slumps, log jams, siltation, ice, road crossings) and other forms of geomorphic evolution are not considered. In the unusual case when a formal hydrological design is done, the armouring is typically deemed to be too costly and the channel is left unarmoured or is armoured with undersized cobbles. Mines often ignore the regional hydrology in their reclamation and allow creeks and rivers to cut into waste fills over time.

Most mines use terraces (benches) on their dump and tailings slopes. They are usually spaced at 30 to 100 m slope lengths. Downslope channels are uncommon – water is allowed to accumulate and spill over the terrace edges. Citing different strategies, some mines tip their terraces in, some out, and some build them level. Inclusion of terraces was an improvement in slope design 20 years ago. but improperly constructed terraces concentrate flow and contribute to erosion, especially gully erosion. However, terraces do have their benefits and a limited number usually need to be carefully designed into the landscape. The terraces need to be tipped in (so that they slope back towards the slope) and the runoff routed laterally to armoured downslope channels (United States Department of the Interior, 1967). Alternatively, the use of landform grading (discussed below) may be employed.

Half of the mines have high percolation rates — especially into coarse waste rock dumps. A few mines have constructed coarse permeable zones to enhance infiltration to limit surface runoff and erosion. Most mines with acid rock drainage (see MEND Secretariat CANMET, 2001) use engineered covers to limit percolation and design methods are improving rapidly (Barbour, 2000).

A quarter of mines visited are at risk to beaver dams blocking a key stream or spillway, flooding large areas or causing reservoir overtopping (see McKenna et al., 2000). Only one of these mines considers beaver activity in the design of creeks and streams. At the six mines that experience beaver problems, staff simply periodically shoot the beavers. Baker et al. (1996) describe catastrophic failure of an abandoned tailings dam in Ontario caused by an unchecked beaver dam.

The hydrology of end-of-pit lake filling is poorly predicted as described later.

Staff at a quarter of the mines visited are experimenting with geomorphic approaches (designing slopes or creeks based on observations of nearby natural terrain or designs) that recognize the geomorphic evolution of the landscape (erosion, gullying, and subsidence). Most of these are in a limited, informal, or experimental way.

Landform grading is being practised or attempted at a few mines, but not systematically and typically without formal hydrologic design. It has been applied successfully to large residential developments in California (Schor and Gray, 1995) for the past 20 years and many of these projects are large even by mining standards. Landform grading breaks the slopes into distinct microwatersheds (usually less than one hectare) so there is little erosion or maintenance. For mining, the most important features landform grading offers are erosional stability and diversity, though in most cases it is driven by aesthetics. Landscape performance of these areas has been good, likely due to high infiltration rates and very small watersheds. Acceptance of long linear and planar slopes and constant-elevation ridgelines for new landforms is waning. Similarly, meandering creeks are becoming preferred to straight, steep-sided ditches.

Groundwater

Groundwater quality is currently a problem for some mines, partly due to vagaries in goals and partly due to uncertainty in predictions, especially when coupled with uncertainties in mine planning and execution. That mines are located in highly mineralized areas and the mining activity exposes the soils and rocks to solute movement and oxidation means that movement of metals and other ions is inevitable (Yernberg, 2000).

On-site (and especially in-waste) groundwater quality is seldom viewed as an issue. Pore-water within tailings structures and waste rock dumps is usually highly mineralized especially at metal mines (Hutchison and Ellison, 1992). This situation seems to be tacitly accepted, perhaps because there are no reasonable alternatives. Prevention of bioaccumulation of metals in reclamation vegetation can be a significant issue (Winter and Redente, 1999).

The point of compliance for groundwater quality monitoring is usually a lease boundary or a disturbance boundary. Sometimes it is acceptable to show a delay of 1000 years before a plume crosses the boundary. Groundwater travel time predictions are often inaccurate, especially where the subsurface geology is poorly understood, and velocities may be much faster than expected. The rationale for the acceptability of poor performance at some distant time in the future is not clear and regardless, the public has become distrustful of many predictions (Sarewitz et al., 2000; Moran, 2000).

Ten percent of mines visited reported concerns with groundwater. A larger number ignored or some even avoided determining their effects on groundwater. Many have monitoring programs, but without remedial options if a plume were detected. Few employ groundwater specialists.

Groundwater is usually only a high-profile issue if drinking water aquifers are at risk. Most mines would benefit from more thorough groundwater management programs.

Soils

Few mines have a soil scientist involved in the design or placement of their cover soils, even though having good soil is a critical issue for successful reclamation. Generally a few trial plots are used to assure reasonable growth of agronomic species – if performance is acceptable, the prescriptive thickness becomes the standard for the site independent of slope, aspect, substrate, vegetation, moisture, or land use. Even with these shortcomings, based on the apparently successful vegetation in most areas, most soils are performing adequately.

Most mine reclamation requires placement of some thickness of coversoil over mine wastes, usually as a combined barrier or cover and as a vegetative growing medium. Many of the minesites had no cover soils and used direct seeding techniques instead. Required coversoil thicknesses ranges from a few centimetres to three metres and thicknesses of 30, 50 and 100 cm are common, with greater depths reserved for problem substrates.

Many mines are moving away from extensive coversoiling. Direct seeding of mine wastes is becoming more common, particularly for soft rock mines and for tailings sand. Often the initial performance of waste rock dumps as growth media is improved by the presence of nitrates left by blasting.

Along with regrading, coversoil placement is usually the greatest reclamation cost. Placing the soils is usually a straightforward mine planning / scheduling task for the mine operation.

One of the main roles of soil in mine reclamation is to form a good growing medium so vegetation can help to prevent or limit erosion. This approach is successful over most of the landscape. Where water flow is concentrated and soils unarmoured, the vegetative cover and coversoil are eroded, exposing the fill substrates below. If the substrates are radioactive or metaliferous, such gully erosion is viewed negatively.

A few mines recognize that these reclamation soil caps act as unengineered covers – their composition and properties have tremendous impacts on site-wide water balances (and hence landscape performance). A fuller consideration of the hydrologic impacts of the reconstructed soil placement and stratigraphy on local and overall landscape performance may yield more optimal designs.

Vegetation

Revegetation is the most advanced area of mine reclamation. Most stakeholders are concerned about having sites that have good, self-sustaining vegetation – for most people, lush greenery is a significant indicator of good landscape performance.

Almost all mine reclamation focuses on revegetation – mostly establishing grasses and legumes and a few work on establishing trees. A few of the sites visited focus on ecosystems rather than just vegetation. But a quarter saw their vegetative efforts as a way to mitigate the disturbance to a point where nature will take over and enhance their efforts to date. While some mines have planted millions of trees, most are hesitant to plant trees, arguing trees are costly and will invade anyway. Island planting schemes from trees, shrubs, or expensive plants are used in some areas. Few mines monitor the influx of volunteer species into reclaimed areas, but where it occurs, most take this as a positive sign of good performance.

Three quarters of the mines visited are using agronomic species for reclamation (usually exclusively). A quarter use some native species. Three quarters are seeing some natural re-invasion of native species, and a third are seeing a great deal. A few mines observe that the performance of areas allowed to naturally invade is better than those formally reclaimed and revegetated (e.g., Biro and Georgescu, 2000).

Attempting to move beyond existing good performance, some regulators (e.g., Alberta Environment) are restricting mines to using native species and requiring patch-like mosaics of plantings to produce more sustainable and diverse vegetation and wildlife habitat. Soil development and ecology are becoming focus areas. Part of the move into these areas likely reflects the fact that existing revegetation practice, although successful, may not meet all the future land use and sustainability goals. Regulators often prefer local native species for revegetation because native species are better adapted to local conditions, wildlife are adapted to native vegetation species, and there are concerns about introduction of exotics into native ecosystems (e.g., Oil Sands Vegetation Reclamation Committee, 1998).

Most mines resist using native species and planting trees because of good success with agronomic grasses and legumes – agronomics are inexpensive, widely available, fast growing, green the landscape rapidly, provide nearly instantaneous erosion protection, are often better at enhancing soil development, reducing net percolation (e.g., Hutchison and Ellison, 1992; Aziz and Ferguson, 2000), and provide more protection against overland flow erosion (Lowdermilk, 1934).

Most jurisdictions specify minimum vegetation productivity levels (e.g., rates of tree growth, harvest yields of agronomic crops) based on comparisons to predisturbance conditions. However, there is widening recognition that productivity strongly reflects management inputs (irrigation, fertilizer, etc.). As a result, there is a move toward a more land-capability approach that focuses more on the science of providing the right kind and amount of soil rather than measuring tonnes per hectare of crop or forest production. This change also permits more ecosystem-based approaches using a variety of initial species. Some jurisdictions, such as Alberta, require compliance with both capability and productivity measures (Oil Sands Vegetation Reclamation Committee, 1998.).

A quarter of the mines are direct seeding waste materials (from 10 to 100 percent of area) to save money. Revegetation typically costs about $2000 per hectare. Resloping often costs about the same. Coversoiling typically costs $10,000 to $30,000 per hectare mostly depending upon thickness. By avoiding placing a coversoil, successful direct seeding can result in a reduction of reclamation costs of 30 to 90 percent.

A few areas of active research seen at the mines are notable. The use of carefully salvaged and placed leaf-litter horizon as a seedbank and source of propagules is receiving more attention, especially for use in island planting. Root inoculation with mycorrhizal fungi is becoming more common (Sturges, 1997). Optimal planting, irrigation, and fertilizing strategies for local conditions are being tested at most sites using test plots or observations of the previous year's reclamation.

Wildlife

Mines typically have a benevolent attitude towards wildlife, particularly large mammals (e.g., elk, deer, moose, sheep) and other charismatic megafauna. The presence of wildlife is a key indicator of good landscape performance to many stakeholders. However, mines have little guidance on how to design their landscapes to create permanent wildlife habitat.

Twenty percent of mines are designing at least some areas of their landscapes to support wildlife – most through selection of initial vegetation planted, others by providing feed, building of rock piles for small mammals or microtopography to support wildlife. Agronomic grasses and legumes often provide good forage – especially in forest regions. Several mines are making integrated regional wildlife plans for their sites, though more are exploring design and field methods.

Some mines experiment with temporary measures for wildlife habitat enhancement including brushpiles, snags (standing dead trees/logs), birdhouses, bat caves, revegetation using alfalfa and grasses, and even bringing in bales of feed in the winter. Results vary – many programs have only short-term value in terms of landscape performance, but high public relations value.

Some mines are considering planting ecosite patch sizes mimicking the range of natural variation (see Bissonette, 1997; Schneider, 1997). While a sound strategy, it is recognized that these plantings are essentially temporary measures – long term diversity is only marginally correlated to initial planting and ultimately comes from a diversity of soils, substrates and topography. Long term wildlife habitat is thus most greatly enhanced by creating diversity of landforms, topography and soils. This aspect of wildlife habitat design at the landscape level is in its infancy.

Wildlife often move *to* active minesites (Barr, 2001). Fences help to keep out hunters, poachers and shy predators, and the miners often share their lunches. The result is that active and reclaimed mine areas often have unusually high density of wildlife. Most mines feature this wildlife in their environmental brochures.

Traditional environmental knowledge

Traditional environmental knowledge is a largely untapped resource, thought it is starting to be incorporated into some environmental impact assessments (Freeman, 1992; Sallenave, 1994) and was sought by a few of the mines visited. It refers to knowledge and skills of local inhabitants who are often aboriginal. First-hand knowledge, lore, and spiritual connections provide a rich background and opportunity for reclamation design. The focus of traditional environmental knowledge for mine reclamation seems to be usually centred on plants (especially high-value medicinal plants), ecology (especially vegetative communities and wildlife), and restoring the land's spirituality. Incorporation of this knowledge in preparing landscape designs to construct the landscape remains difficult but important to successful reclamation at many sites (Johnson, 1992).

3.5 Other elements of landscape performance

While not specific to any particular discipline, there are other design and construction elements that are important to achieving landscape performance and closure goals and are described below.

Human health and safety

Just about all mines see the need to protect human health and safety. Efforts focus on removal of equipment, buildings and infrastructure, removal of barrels and chemical and radioactive hazards, and protection for underground openings. Creating landscape that provides for human health and safety is usually the highest goal. Mines take this responsibly seriously and are reasonably successful. Many mines improve conditions to the point where they are safer for humans (and wildlife) than the surrounding landscapes (for example, removal of highwalls, rounding pit crests to reduce risks of falls, keeping radioactivity from mine spoils to levels below background, keeping water quality below background levels, barricading unsafe areas, etc.) Efforts on safety are important as there are approximately two dozen fatalities every year at abandoned US mines (Mine Safety and Health Administration, 2002), half involving children, many involving drowning in mined out pits and quarries and many involving falls down shafts and over pit crests.

Concern for the health of future users of the land and those downwind and downstream are similarly very important to just about all mines and regulators.

Aesthetic considerations

It is becoming increasingly important for mining landscapes to be aesthetically pleasing to stakeholders. People seem interested in seeing varied ridgelines, avoidance of planar slopes and straight lines, diversity of vegetation, and removal of roads, powerpoles, and scrap metal and lumber. Often this is part of a desire to see pre-disturbance conditions restored.

Aesthetics is a new topic coming to mine reclamation. Visual aesthetics tends to dominate such talk, but a well-reclaimed landscape appeals to all senses. Miners complain that aesthetics are hard to regulate but at several mines it is as easy as presenting an artist's rendition to people at public meeting and getting their buy-in that this would provide an acceptable looking landscape. About 20 percent of mines are experimenting with aesthetics in their reclamation. Some guidance is available (Litton et al., 1974; Carlson, 1977; British Columbia Ministry of Forests, 1995; Merritt, 1997). While consideration of aesthetics should complement overall landscape performance and design (e.g., Gelernter, 1997), care must be taken to avoid compromising physical stability and other important goals while trying to enhance aesthetics.

Construction of landscapes

The construction of landscapes – the fieldwork required to achieve the designs – is well handled. In most cases, it is the mine operations group that performs the major earthworks and this work is handled efficiently, especially in the reclamation of large tracts of land. The operators become skilled at achieving the desired accuracy and take pride in their work and are innovative.

As described above, the finer details, such as establishing creeks, fixing bare areas, and other small repairs is generally not being attempted, perhaps because the large mine equipment is economically mismatched to such tasks.

At some mines, contractors handle all reclamation work. When these contractors are also involved in design and have the support of stakeholders and regulators, it is a powerful combination. Traditional miners often feel that their expertise is moving materials at mining scales and leave the reclamation side to the specialists. However, at well-run strip-mining sites, it is difficult to separate mining and reclamation activities – they are part of a seamless continuum.

3.6 Monitoring and maintenance

Monitoring and maintenance of all reclaimed landscapes is a critical element of successful reclamation and it has become apparent that most sites will require long term monitoring and maintenance to continue meeting their closure goals well into the future. Mines and regulators are becoming aware of the ramifications. Typical monitoring and maintenance efforts at the mines visited is described below.

Monitoring can be divided into four types. Compliance monitoring is that required by regulators. Operational monitoring is that needed to support the operation. Research monitoring is intensive monitoring of smaller areas towards answering specific questions that ultimately impact on landscape performance or cost. Certification monitoring is that required to demonstrate good ongoing landscape performance for eventual certification. Methods and goals for each vary.

Few mines handle reclamation monitoring and maintenance well and systematic documentation of these activities is usually lacking. The use of geographical information systems (GIS) for documentation of reclamation, monitoring and maintenance activities is employed at a few mines (e.g., Lang, 1998) and is become more widespread.

Monitoring during operation

Few mines formally monitor performance of their reclaimed areas during operation. The two types of monitoring that do occur are research monitoring of small vegetation test plots and informal drive-by monitoring where the reclamation specialists periodically observe reclaimed areas. Periodic inspections by regulators often provide the mine with a list of deficiencies (or lack there of) and forms a sort of monitoring. Compliance monitoring is well done where required, but is done at the minimum level required by regulators.

A quarter of the sites visited are doing some streamflow monitoring and a similar number monitor groundwater wells. A quarter monitor erosion, typically only visually. Half monitor vegetation performance to some degree and a quarter monitor for wildlife. A few mines use remote sensing as part of their monitoring program – the availability and affordability of 1-m Ikonos satellite data as a monitoring and communication tool shows promise.

A quarter of mines have research plots and a similar number of offsite natural reference areas. A quarter of mines have good climate data available on site or nearby but half don't use numerical climate data in support of reclamation activities.

Formal monitoring of landscape performance does not usually start until the need for long term maintenance becomes a reality. For a variety of reasons, a long term landscape maintenance program should begin during the exploration phase of a mine's development, and one that continues until all liability can be discharged.

Maintenance during operation

Planned maintenance activities such as fertilization or irrigation seem to be well handled. They are part of the reclamation cycle and are done on a yearly basis for the first few years after reclamation. The initiation of vegetation is also well handled – if the vegetation fails to "catch," the area will often be revegetated again the following year. Areas that fail a compliance measure (such as surface-water quality) are usually dealt with quickly, with a focus on short-term solutions.

At most mines, physical repairs to the landscape are unusual. Fixes to small slumps, gullies, flooded areas, and small areas of poor vegetation growth are delayed indefinitely unless regulators pressure the mine staff. Large tracts of land remain incompletely reclaimed pending these small fixups.

A strategy employed at a few mines is to allow nature to identify the weak areas in the landscape, then focus on providing really strong fix-ups of these areas. For example, if a gully forms, the gully is repaired to withstand a much larger event. If areas are showing poor vegetation performance, the soils are analyzed and different species more suitable to that specific location are planted or the soil is improved. In this way, the landscape can be economically and progressively upgraded focussing on the weakest areas and results in a declining maintenance approach and allows adoption of new technology and experience with time.

Post-closure monitoring and maintenance

To continue to provide acceptable performance, about three quarters of the mines visited will require some kind of long term (perhaps declining) maintenance, ranging from periodic fix ups as required to daily maintenance such as water treatment. Monitoring and maintenance are often a method of reducing the long term liability.

3.7 Design and performance of various mining terrain units

Terrain analysis is used to categorize natural landforms for engineering (and other) purposes (Way, 1973). This process can be extended to elements of anthropogenic landforms, including mining landforms. Using this classification scheme, generic landscape performance of various terrain units can be described. This section provides a qualitative evaluation of the major terrain units and other landscape elements typical of minesites. Table 3-3 provides a summary and scorecard, plus an indication of typical maintenance levels that will be required to achieve acceptable long term performance under current practice..

Closure infrastructure (roads, powerlines, pipelines, water treatment facilities, fences)
Sites that require long term monitoring and maintenance require infrastructure such as roads, powerlines, substations, pipelines, and water treatment facilities. Fences and gates are used to limit access to sites or to underground openings.

Fences and infrastructure are performing well, but require periodic maintenance. Vandalism and theft are common concerns at most sites. Where used, these facilities will have to be monitoring and maintained periodically, and decommissioned and removed if the sites are abandoned. Remote mines often need to maintain long access roads, powerlines, and sometimes water and gas pipelines.

Shafts and portals
Underground mines have shafts and portals that remain after closure. Designs for sealing of shafts and portals has received a lot of attention in the literature and is usually well done. Sometimes gates are employed, while other areas receive large concrete plugs. Gated shafts often support very large bat populations.

A dark cloud for this technology is the ingenuity of trespassers. Quite a few mines, especially in the US, have had people remove or bypass these portals, leaving them open for others to enter. These trespassers use acetylene torches to cut through gates, explosives, even drill and blast methods to bypass the plugs, presumably to be able to explore the old mines, or seek treasure. There is extreme danger to these trespassers, their rescuers, and others who exploit openings (Nevada Commission on Mineral Resources, 2000).

Pitwalls
Hardrock pitwalls are generally left unreclaimed, largely because they are difficult to reclaim and most jurisdictions do not require it. Some mines have successfully argued that this terrain unit provides escape terrain for wildlife or nesting for birds. Mines are reducing hazards to people and wildlife inadvertently falling down the pitwalls by installing extensive fences or berms along with signage. Some are rounding the pitwall crests.

All pitwalls show evidence of active spalling and a quarter of those visited have semi-active landslides — the hallmark of a well designed mining pitslope. Hazards are often similar to those of natural cliffs in the region.

Most hardrock mine pits fill with water to become lakes and the pitwalls continue to spall. The semi-active geotechnical slope failures are in some cases made more stable due to pit filling and other cases made less stable. Spalling and landslides present hazards to users of the lake and the potential to cause reservoir waves which may endanger users of the in-pit lake or downstream facilities.

Most jurisdictions recognize that pitwalls will remain a geologically active historical remnant of mining. Some (especially American jurisdictions) require expensive buttressing to full height. Soft rock highwalls (coal or oil sands) are more often resloped or blasted to lower angles and reclaimed.

End-pit lakes

End-pit lakes are common – almost every open-pit mine will have at least one. Interestingly, most mines planning for an end-pit lake view it as a unique and surprising challenge.

Unfortunately, the filling rates and final elevations of end pit lakes are presently poorly predicted (see Table 3-4). Most pits fill much faster than predicted (often by a factor five). Others stabilize at water levels that are too high or two low, greatly affecting the amount of littoral zone and, hence, the end land use and recreational potential of the lake. Almost all end-of-pit lakes (10 of 12 visited) showed performance that was significantly different than predicted.

Errors in the water balance have resulted from failure to consider groundwater recharge and from failure to consider the overall watershed feeding the lake (including what water will be pumped from around the minesite). The poor prediction of end-pit lake filling rates and elevations means that water treatment plans often have to be moved forward by 10 or 20 years and the treatment plants built and commissioned quickly.

Some guidance on end pit lakes is available from Lewis (1999), Kempton et al. (2000), and Shevenell (2000) who suggest estimating uncertainty of predictions and using data from initial filling to calibrate surface water, groundwater, and geochemistry models.

Often, end-pit lakes are used to store large annual volumes of water treatment sludges and production may continue over centuries (e.g., Environment Canada, 1997). Long term sludge management plans are generally lacking as is the impact of the sludge on end land uses for the end pit lake or landfill areas.

The limnology of end-pit lakes is also difficult to predict. Many hard rock end pit lakes have significant water quality issues that are very complex and difficult or impossible to accurately model (Moran, 2000). Formations of thermoclines, haloclines and chemoclines need consideration. The water balance is often difficult. Most lakes have small littoral zones, and so have clear water and low productivity. Overturning remains a concern for many lakes. Most people desire to see fish in end pit lakes; the absence of fish may be seen as a failure of this terrain unit.

As mentioned above, pitwall spalling represents a hazard to people and wildlife utilizing the lake. Larger pitwall landslides also present hazards. Stability of in-pit dumps due to lakeshore erosion, long term saturation, or weathering may result in large landslides.

Dump slopes – at repose

Dumps (overburden storage areas) are sometimes left at their angle of repose (often ~35°) in the final landscape. These slopes are usually comprised of coarse rock, which accept virtually all precipitation as deep percolation. Aside from the fact that it is rare to see much vegetation on these slopes (Leavitt et al., 2000), many are performing well, similar to natural talus slopes. However, most repose slopes offer little utility with respect to land use.

Some repose slopes are vegetated, particularly ones that have a finer component and some cohesion. However, these slopes may be susceptible to shallow slip failures and solifluction-like movements, probably related to local variability in the permeability and concentrations of shallow groundwater flow and the associated loss of cohesion.

If weathering causes a reduction in friction angle (with the related generation of fines), geotechnical and erosional stability may be problematic. Long term seismic stability of dumps at repose may be an issue. Leaving dumps at their angle of repose slopes are often rejected outright by regulatory agencies, however, it may be possible to make a technical case for leaving some slopes at repose if the case can be made that they will exhibit acceptable landscape performance and there is evidence that under certain conditions (and where goals are modest) and in certain regions that this can be achieved.

Dump slopes – resloped / terraced

Most mines have dump slopes that are resloped to angles of 2H:1V (26°) or flatter. Terraces are usually included in the slopes, but the technical reasons for the terraces are often not fully understood by the designers. In fact, their use is usually prescribed by regulatory agencies.

Most resloped dumps are performing well. A few gullies will form over time (particularly in finer grained materials) but most do not impact significantly on overall landscape performance. Slumps at the toe happen occasionally, particularly if the dump is oversteepened by having a toe ditch built too close.

Vegetation on these slopes is usually easy to establish, except in desert areas.

As described above, the design of the terraces remains a problem.

Berms also give an artificial look to the landscape, though visual aspects of their geometric regularity is often reduced if a dense tree cover grows.

Quite a few mines are experimenting with forms of roughening dumpslopes, creating small mounds and hollows to increase topographic, soil moisture, and vegetative diversity. These seem to be acting well, despite not being formally designed. If the watersheds are small enough, medium scale ridges and swales area being effectively used at several mines as a form of landform grading that has both good erosion performance and topographic diversity as discussed above.

Microtopography is a scheme that is being more widely used. Instead of leaving planar slopes, 10 to 20 centimetre holes and mounds and 10 to 20 centimetre high downslope ridges are being incorporated into slopes. This creates microrelief and changes in microaspect for the slopes that enhances moisture retention and leads to improved plant growth. This work is in its early stages and is being demonstrated rather than researched. Suitably employed, erosion may also be reduced while enhancing wildlife habitat.

Poor slope performance is often related to gullying caused by ponded water that have overtopped the top plateau as described below or exposure of sterile, radioactive, or highly mineralized substrates..

Dump plateaus

Most mines have dump plateaus – the large, flat areas on the top of dumps. Dump plateaus are usually performing well despite the lack of technical design. They are capped and vegetated, and the vegetation performs well. Erosion on the plateaus is small. Most precipitation infiltrates or evapotranspirates – runoff is often small and infrequent.

In some cases, differential subsidence leads to the formation of shallow ponds and wetlands (or just puddles) on the tops of these dumps, particularly finer grained ones. This can result in wet soil conditions and sometimes to overtopping events leading to slope erosion as described.

Where percolation is small and ponding (or salinization) is problematic, measures to enhance percolation or surface drainage may be required. These may include creating a bowl shaped upper surface and carrying the runoff water down a predefined armoured channel – often created from an old haul ramp. Other measures may include creation of a hummocky top surface to provide topographic diversity for diverse soil moisture conditions. Hummocks may also add to wildlife habitat values. Doming to force water from the plateau over unarmoured slopes should be avoided – the slopes have a hard enough time dealing with the rain that falls on them directly.

Dump plateaus – engineered covers

Most mines with acid rock drainage concerns use engineered covers to limit annual percolation and hence reduce (and prolong) acid release and water treatment costs. Covers are sometimes designed to shed water, most newer ones are designed to store and release water through evapotranspiration (see MEND Secretariat CANMET, 2001).

Engineered covers are complicated to design and construct – mines are having difficulty in providing reliability in design, construction, and performance. Some mines avoid placing engineered covers on waste rock dumps due to reductions in their efficiency due to cracking from differential settlement of the dumps.

Many dumps with engineered covers to limit deep percolation fail to reach the desired percent infiltration goal. Macropermeability effects means that many mines are able to reduce percolation rates to 10 to 15 percent of annual precipitation, often two to three times higher than the design expectation. Small changes in percolation rates can have a dramatic effect on water treatment costs or passive treatment system performance.

Vegetation usually performs well on these engineered covers, but sometimes too well – volunteer trees are often removed periodically to maintain cover integrity from tree roots. Good long term performance of most covers is probably contingent on periodic maintenance in most cases.

Rockfill dams and drains

Rockfill dams are common as tailings starter dams or as permanent dams to contain tailings. Rock drains are common in mountain coal operations as pervious valley fills move across creeks.

Short-term performance of these features appears to be good, though they are sparsely vegetated. Where the rock generates acid rock drainage (or other metals), remediation requires long term active water treatment downstream. Where these act as dams, long term monitoring and occasional maintenance is indicated.

The key to the use of these materials in dams and drains is to ensure their long term stability under weathering, to ensure that they are not contributing to unexpected leaching and that the need for some long term monitoring is accepted.

Tailings slopes

Slightly less than half the sites visited have tailings dams – most coalmines do not have tailings dams and many uranium mines have remote dams at regional mills. Many tailings dams are constructed with at least some of the downstream face constructed of tailings sand (often silty sand or silt) which generally has both poor infiltration and water holding capacity.

The result is that it is often difficult to create a continuous healthy vegetative cover on tailings sand slopes — rilling and gullying is common. Some areas experience minor slumping (especially in areas which have slightly finer tailings), and some exhibit evidence of solifluction-like creep behavior. Areas that need irrigation to establish the cover are susceptible to gully erosion due to sprinkler pipe leaks and breaks. Where seepage exits at the toe, vegetation is usually sparse and spring sapping (rill or gully erosion caused by artesian seepage) can sometimes be observed. Slopes constructed of cycloned tailings sand fare slightly better. In many cases, the pore-waters contain constituents of concern that must be contained and restrict land use.

There is also a concern about the effects of animal grazing or erosion by all-terrain vehicles on some of these tailings slopes. The vegetation cover is often fragile. Once a gully is able to cut through the vegetation or soil cover, erosion occurs rapidly, and most of these gullies are not self-healing.

The result is that most tailings sand slopes are performing poorly and have doubtful long term performance in the absence of periodic maintenance. Alternatives to having tailings on the downstream slope may be useful to consider, given the cost and intensity of maintenance of these slopes. Where already built or being considered for use, given the poor track record of tailings slopes, extra measures such as conservatively designed surface-water drainage systems, armouring with rock or rocky soil, additional capping thicknesses, long term internal drainage measures, and long term maintenance should be considered to improve their performance.

Tailings beaches

The sandy beaches, especially where unsaturated seem to be easy to reclaim, and are sometimes direct seeded or capped with a thin layer of reclamation material. They are performing well.

Beaches that have a water table near the surface may exhibit trafficability problems but, once reclaimed, seem to perform well. Long term salinization and metal uptake remains a concern for those with long term water tables near the surface. At some oil sands mines, hummocky ridges are planned to provide areas with lower water tables (separated by broad wet swales).

Dusting from tailings areas during active operations is a concern for most mines but can usually be brought under control through vegetative, soil, or water cover soon after closure and is not usually a long term closure issue.

Like dumps and tailings slopes, the beaches (the bulk of the tailings sand deposit) provide a long term source of potential groundwater contaminants.

Tailings – soft areas

Most mines with tailings ponds produce a saturated fines zone (fine tailings, sludge, slimes) at the distal end of the beaches that is extremely expensive to reclaim. Typical costs are about $200,000 per hectare (10 to 20 times normal reclamation costs) to stabilize and reclaim these extremely soft deposits (McKenna, 1999). After reclamation, subsidence and ponding continue to be a long term concern with no ready solutions. Water treatment costs for the process-affected waters at closure can also be immense and unexpected. End land use values for these areas are often low, due to ongoing concerns about trafficability, safety, salinization, and metal uptake by plants.

Soft tailings stabilization and reclamation is an area that requires considerable research and innovation. Hydraulic capping of these sediments with a free-draining sand may be required and may be affordable if planned early enough. Water capping is discussed below. Methods to minimize the area of soft tailings at the surface of reclaimed tailings ponds is needed. In some cases, reclamation of soft tailings can cost more than the entire operational tailings costs. Avoiding traditional tailings ponds, or at least minimizing their size, may be an outcome in a few situations.

Tailings ponds

Sometimes tailings ponds are turned into shallow freshwater lakes, through water capping, and with considerable short-term success. A spillway cut into bedrock is usually a requirement for abandoning a tailings pond. Sometimes tailings are placed in the bottom of end pit lakes. This approach is used to isolate acid generating tailings from oxygen. The geochemistry of these lakes is difficult to predict. Radon gas release may be a concern for radioactive tailings.

Rates of consolidation seepage from these soft deposits is notoriously difficult to predict. This uncertainty, combined with multiple complex threshold mechanisms can have a profound influence on geochemistry, oxygen availability, nutrients, and fish.

Despite these efforts, it seems likely that these ponds will require periodic inspection and maintenance. Though they provide useful landscape elements, their future performance remains uncertain. Water capping of acid rock drainage tailings remains a leading technology which is closely being monitored for long term performance. Water treatment at the outlets is usually required. Designing and constructing these facilities to handle large precipitation events can be challenging.

Where no pond is to be left behind, it is typical to cut a deep notch in the dam to prevent water accumulation.

Rivers and creeks

Almost every mine will have to re-establish a creek or river. Some will need to construct tens of kilometres of watercourses. As described above, few mines visited have a formal design for any rivers or creeks. Of the few that have been constructed, only a couple received formal design; most are simply field fit.

However, present performance of almost all of the few rivers and streams seems good. Bank erosion and solids loading to streams seems minimal. Suitability as fish habitat for most seems minimal. Few of these watercourses are likely to maintain their good performance during even modest floods. Many have highly erodible substrates and will require extensive repairs after such events.

These streams need to be designed, construction needs to follow design, and periodic monitoring and maintenance, particularly after extreme events, is likely required for ongoing good performance. There seems to be wider recognition that not all desired environmental values can be replaced when relocating, diverting, or building new streams. In some cases, despite ore sterilization, mines are permitted to avoid disturbing streams, particularly fish bearing ones.

Wetlands

Some mines have or plan to have wetlands. Their use is largely a matter of the regional geography. The use of wetlands in mine reclamation is a popular topic, especially for water treatment, but also for avian and wildlife values.

The few wetlands observed seemed to be performing well. Most are classified as marshes – they are predominantly open water and are fringed with emergent and semi-emergent aquatic vegetation. Wetlands often provide good habitat, help to trap sediment, and attenuate flows. The key is the hydrology of the wetlands which is often difficult to predict in advance.

Some mines are interested in the potential of wetlands as bioremediators of everything from sediment to naphthenic acids, salts and metals. Wetlands designed as bioreactors typically have a series of long parallel channels and a very civil-engineered appearance. The long term performance of such systems is highly uncertain (Eger et al., 2000) unless monitoring and maintenance is planned. Concerns include reversal of reactions (liberating metals), metal uptake of vegetation in turn consumed by birds and wildlife, bio-accumulation, flooding by beaver dams, and winter and freshet performance.

Opportunistic wetlands (Alberta Environment, 2000) often form naturally on reclaimed land and benefit from elements of self design (see Mitsch and Jørgensen, 1989; Jørgensen and Mitsch, 1989; Odum, 1989). Marsh-type wetlands could be more widely incorporated into reclaimed areas as they have a large number of benefits and seem to be easy to create though about half of constructed wetlands fail to meet their intended functions (Mitsch and Gosselink, 1993).

Sedimentation ponds and checkdams

Just about all mines use sedimentation ponds and checkdams for operational sediment control and many envision using these structures in the final landscape.

Offsite improvements

As a part of the permitting negotiations, many mines are offering or required to "improve" an off-site natural area, away from active mining, to offset mine disturbance (for example, fish habitat improvement in an existing creek, or creation of an oasis in a remote desert). Many of these improvements likely degrade other landscape values and most are likely not self-sustaining.

3.8 Landscape-scale performance

The performance of each mine at the landscape scale based on a brief site visit is difficult to ascertain. One also has to postulate criteria for overall performance. One could suggest that whole-landscape performance could be acceptable if off-site effects (usually fluxes) were acceptably low, the site was safe and seems capable of meeting some low level of landscape use (in many cases, just being green), that risks of future catastrophic events were small, and maintenance levels were acceptably low.

Based on these simple criteria, three quarters of the sites visited seem capable of meeting this standard. The ones that don't are ones that have overlooked major components such as groundwater plumes, lack of major surface-water drainage systems, inability to establish a reasonable vegetative cover over large areas, or were simply abandoned in an unreclaimed state.

Acceptable landscape performance based on simple overall criteria seems obtainable. But meeting specific goals and having good performance for each areas of the site will be rather challenging for most mines. This discrepancy suggests:

- with modest efforts, landscapes can be reclaimed to at least "do no harm", targeting a minimum goal of being "safe and stable".
- having good performance everywhere in the landscape is difficult. It comes down to a question of scale – at what scale is good landscape performance required?
- incremental increases in performance are both expensive and require higher levels of design effort and often higher levels of monitoring and maintenance.

This discussion highlights one of the major findings about landscape performance, one that is seldom considered explicitly. Landscape performance depends on the scale of the inspection. At the landscape (or regional) scale, which encompasses the whole disturbance and possibly the surrounding areas, reclaimed landscapes can be made to perform well. At the landform scale (typically 100+ hectares), most areas will perform well while some areas will require more effort and attention. At the micro scale (say one square metre), most mines will have many areas that will not pass (for example, they will be actively eroding, they will have elevated levels of some undesirable chemicals or ions, they may be unvegetated). So any question of assessing landscape performance should deal explicitly with scale.

Failure to specify performance based on scale makes mines liable to the whim of regulator. It essentially confirms the notion of unlimited liability. Clearly, a regulator would not fail a landscape based on poor performance of a single square metre of landscape, but how many and what size of poorly performing area would constitute failure? What minimum size of deficiency would have to be remediated?

3.9 Meeting goals reliably

There is little assurance that mines will meet their reclamation and closure goals, and even less that long term performance will be acceptable. This is caused by overselling the intended performance on the reclaimed landscape and by uncertainty in trajectory and behaviour of the landscape under unknown and perpetual forces. This uncertainty in meeting long term goals and the associated liability contribute to the certification barrier – the near lack of certified reclaimed land.

Mines have the habit of promising too much from the reclaimed landscapes and need to remember not to promise what cannot or will not be delivered. In particular, professionals need to counsel their companies and clients on making what may end up being extravagant claims about the landscape including such items as promising an early return to pre-disturbance productivity levels, maintenance free status and zero erosion.

In fact, not much can be promised – there are simply too many failure mechanisms and interactions between mechanisms to be able to provide reasonable assurance that the landscape will meet any but the most basic of goals. A mechanism of setting modest goals and designing landscapes to meet these goals reliably is clearly required. Perhaps more importantly to mining companies and regulators, a mechanism for transferring liability of well-constructed sites is needed.

One may argue that society might not tolerate a reduction in mine reclamation goals and regardless, that mines should be trying to achieve higher goals – that the landscape performance (along with the research, consulting, and contracting sectors) would benefit from such a strategy. This strategy is employed implicitly at most mines – corporate goals are usually greater than regulatory requirements. A potentially successful strategy is to attempt to achieve higher goals, but only be accountable to stakeholders and regulatory agencies for goals that are certainly achievable and reasonable.

Most mine landscapes should have a core team of specialists, either on staff or available as consultants to provide planning and design services for the construction and reclamation of their landscapes. An ideal team would include specialists from the fields listed in this chapter: geotechnical, surface-water hydrology, groundwater, soils, vegetation, wildlife, and traditional environmental knowledge. A strong technical leader who can help bind the team together is usually needed. Other specialists, such as geochemists, ecologists, undermining specialists, may be required on a case by case basis. This team should guide each mining landform through its life, from conceptual closure plan, through basic and detailed design, construction, reclamation, decommissioning, certification, and custodial transfer. Levels of effort from each specialist will vary over the life of the landform, depending up its stage in life. Mine sites will often have five to fifteen landforms in various stages along the way. Landscape design is a significant undertaking, but necessary for successful reclamation – and in particular to produce acceptable landscape performance and reduce a mines environmental liability.

Landscape engineering, developed in Chapter 5, takes an even broader view of landscape design and involves the integration of all technical specialists and activities such as planning, investigation, design, construction, operation, assessment, research, management, and training.

3.10 Conclusions

Landscapes and mining landforms are receiving considerable geotechnical design attention, but few receive attention from other specialists such as hydrology, groundwater, soils, vegetation, wildlife, and traditional environmental knowledge. Attention to surface-water hydrology is particularly lacking.

Despite the lack of a formal integrated approach, most landscape terrain units are performing moderately well, especially if measured against modest goals, at least in the short term. Problem units include tailings slopes, soft tailings areas, rivers and creeks, end pit lakes, and groundwater plumes.

A more integrated approach towards landscape design is needed throughout the life of each landform. Specialists from each of the core areas, as well as other site-specific specialists need to form a team that guides development of each landform from early planning stages through to custodial transfer.

Some specialties are more developed than others with respect to landscape design. Geotechnical areas are well developed and often well applied, surface-water hydrology and groundwater areas are well developed but infrequently applied, soils and vegetation are well suited for modest efforts, but more work is required to improve upon them, particularly focusing on diversity and ecosystems. Rational design for wildlife habitat remains to be developed. Traditional environmental knowledge is an almost completely untapped resource. A few mines are attempting to integrate these disciplines in landscape design.

Most terrain units will require at least some low level of long term, perhaps declining maintenance to meet even modest landscape goals. Though a worthwhile staring goal, the notion of walking away from a landscape once reclaimed should be considered the exception rather than the rule.

A more rational, careful system of design would yield better performing landscapes, cheaper, and with higher degree of reliability – something sorely needed by the mining industry.

Given that in almost every instance, at least one mine visited is tackling at least one aspect of landscape design and there is usually at least one example of good landscape performance for each terrain unit or landscape element, there is reason for optimism. Little new needs to be invented. What remains is a commitment from management to support integrated teams working on landscape design and working towards successful reclamation, and a formal but flexible approach that will result in successful reclamation.

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Table 3-1 Landscape design and performance rating system for Tables 3-3 and 3-4

Subjective Rating	Landscape design	Landscape performance
A	• High level of design is typical • Goals well defined • Design methods available	• Good landscape performance nearly universal • Very likely to meet long term goals
B	• Above average design is typical • Goals well defined	• Good landscape performance common • Likely to meet long term goals
C	• Modest level of design is fairly common • Goals declared but poorly defined	• Modest landscape performance • Likely to achieve at least modest goals
D	• Areas usually not designed • Goals poorly defined • Present methods have low reliability	• Substandard performance common • Goals undefined • Significant consequences of poor performance common
F	• No design or misleading predictions • Goals poorly defined or presently unobtainable • Existing methods inadequate	• Poor performacne nearly universal • Goals unachievable • Severe consequences of poor perfomrance common

Table 3-2 Summary of current design efforts for landscape design experts

Discipline	**Current design effort** **(rating: comment)**	**Current performance** **(rating: comment)**
Geotechnical	B: High level of design effort usually applied, especially to the construction phase	B: Geotechnical instabilities pose few problems. Subsidence may be a sleeper issue.
Hydrology	D. Techniques are available but seldom applied	F. Hydrology is the number one issue for most mines.
Groundwater	C. Usually accounted for and monitored.	D. Often poorly managed and remains a significant liability
Soils	C. Usually fairly well handled by non-specialists	B. Soil performance seems surpassingly good.
Vegetation	C. Well handled, but ever increasing goals, especially moving towards re-establishing ecosystems	B. Vegetation performance is usually quite good, outside of desert areas.
Wildlife	D. Applied successful only in a few minesites, goals usually poorly defined, too much focus on short-term effects.	B. Despite mixed efforts, wildlife seem to flourish on reclaimed sites.
Traditional environmental knowledge	F. Not being considered at most mines, the few that are finding understanding and incorporation difficult.	C?. Natural invasion often brings in desirable species. Goals very poorly defined.

Table 3-3 Summary of landscape performance observations by terrain unit

Landform	Current design effort	Typical performance	Significant issues			Likely level of long term maintenance		
			During planning and design	During construction	For long term maintenance	Walk-away	Periodic maintenance	Scheduled maintenance
Closure infrastructure	C: Traditional civil design	C: Usually requires long term maintenance. Needs protection and repairs from vandalism, sabotage, and theft.			✓		✓	✓
Shafts and portals	A: Carefully sealed in most cases	B: Generally excellent, except where trespassers destroy or bypass them.			✓	✓		
Pit walls	C: Left unreclaimed	C: Accepted low levels of performance. Concerns about rock fall and landslide hazards.				✓	✓	
End of pit lakes	D: Varying levels of design from various specialists	F: Almost impossible to predict filling rate, long term levels, long term performance. Needs more effort and research and a more conservative approach.	✓	✓	✓	✓	✓	
Dump slopes – at repose	C: Undesigned	C: Generally good, but only if expectations for vegetation are low.				✓		
Dump slopes – terraced	D: Usually prescribed design for angle and slope length	C: Most are showing good short term performance despite lack of good hydrologic design.	✓	✓		✓		
Dump plateaus	C: No special design	C: Good but need to prevent overtopping and subsidence puddles in some cases.	✓	✓		✓		
Dump plateaus – engineered covers	B: High level of technical design and construction	C: Good but improved predictability of percolation and long term maintenance requirements	✓	✓	✓		✓	
Tailings slopes	F: Only designed for geotechnical stability	F: Generally poor vegetative and erosion performance; almost impossible to reclaim	✓		✓		✓	✓
Tailings beaches	C: No special design	C: Good, especially if not saturated.	✓			✓		
Tailings – soft areas	F: Brute force capping techniques, empirical field design	C: Marginal once reclaimed. Concern about subsidence and leachates.	✓	✓	✓	✓	✓	

Land-form	**Current design effort**	**Typical performance**	**Significant issues**			**Likely level of long term maintenance**		
			During planning and design	**During construction**	**For long term maintenance**	**Walk-away**	**Periodic maintenance**	**Scheduled maintenance**
Tailings ponds /dams	C: Considerable hydrologic and fisheries design	C: Good short term performance. Concerns about long term biological and geochemical performance.	✓	✓	✓		✓	✓
Rivers and creeks	D: Usually undesigned, occasionally highly designed	D: Almost never designed, when designed, construction does not follow plans, long term stability in doubt.	✓	✓	✓	✓	✓	
Wetland	C: Most undesigned, treatment wetlands highly designed	C: Good performance where little is asked of it. Concern about long term performance of "treatment" wetlands.	✓	✓		✓	✓	
Sedimen-tation ponds and check-dams	C: Modest design	B: Good when well maintained.			✓		✓	
Ground water plumes	C: Varying degree of design, mostly for barriers or plume velocity prediction	D: Often poorly managed, greatest concern is ill-defined goals.	✓		✓	✓	✓	✓

Table 3-4 Hydrologic performance of end-pit lakes

Mine	Performance	Reason	Impact
Lee Ranch	Filling slower than expected		
Brenda Mine	Pit filled 4x faster than predicted	Incomplete surface-water balance	Water treatment plant cost advanced by 15 years
Gibraltar Mine	Pit filling several times faster than expected	Did not fully consider groundwater discharge rates	Advance need for water treatment if mine doesn't reopen
Equity Silver	Pit filling 2x faster than predicted		Affects water treatments and sludge disposal plans
Island Copper	Filling 2 to 4x faster than expected	Filling channel to sea over excavated?	None
Greenhills Coal	Okay, but no schedule predicted		Pit filling schedule not important to operation
Bell Mine	Pit filling on schedule	Small islands of known watershed side	Closure plans on schedule
Granisle			
Highland Valley Copper	Trojan Pit filled to higher elevation than predicted		Destroyed planned littoral zone, no fish
Tent Mountain	Pit filled to lower elevation than predicted		Outflow inactive (probably good)
Quarry Lake	Final elevation seems okay		
Ohio State University wetland	Elevation and flow rates carefully controlled	If not controlled, poor predictability recognized	Active monitoring
Syncrude	Tailings substrate in lake densifying much faster than predicted	Uncertainties in mechanisms and predictions, new mechanisms	Affects tailings volumes and may affect future environmental performance of lake
Summary	*Pit filling usually faster than expected and final elevation mispredicted*	*Poor understanding of site water balance, failure to take a more conservative approach*	*Planning, economics, and intended land uses are often severely affected*

Chapter 4

Successful reclamation

4.1 Introduction

All active mines carry out reclamation but few carry out *successful reclamation* – reclamation that supports the mine's operational and corporate objectives, allows certification and transfer of liability, and can be reasonably assured of providing acceptable long-tem landscape performance including protecting environmental values.

This chapter includes an overview of successful reclamation and rates the Canadian mining industry with a simple scorecard. Challenges as reported by mine staff during visits to 69 mines are described along with examples of innovations that are occurring now and examples of successful implementation of most of the dozen elements of successful reclamation. Finally, a path forward it proposed including methods to handle current shortcomings.

Despite some good reclamation and vast sums of money and effort invested in reclaimed landscapes and research, the mining industry appears to be performing poorly at the three major aspects of successful reclamation, potentially putting the Canadian mining at industry at risk. Changes are necessary to allow (and encourage) mines to meet their covenant of "temporary use of the land" – something presently lacking. The mining industry is working to improve its environmental performance and it is hoped that the ideas and elements of successful reclamation presented here will be a useful contribution to these efforts.

4.2 Methods

Three activities were undertaken to better understand the present state of mine reclamation, how it is benefiting the mining industry, and how it could be made more successful.

First, between 1995 and 2000, 69 mines were visited to better understand the current state of practice of closure planning, landscape design, and to observe landscape performance. Chapter 2 describes the state of closure planning practice (and provides detailed information on the breadth of mines visited), Chapter 3 describes the state of landscape design practice and landscape performance. Appendix A provides a summary of the mine visits. Part of the purpose of the visits was to provide a compendium of challenges either stated or observed at the mines and of novel concepts that the mines are employing.

Second, the author had numerous discussions with mine reclamation and closure specialists in Canada, the US and Germany who provided insight into areas of concern and potential solutions.

Third, the author hosted a workshop as part of 1999 CIM Annual General Meeting in Calgary which included a dozen reclamation specialists from across Canada. Elements of successful reclamation were presented and discussed and the group scored the Canadian mining industry.

4.3 Literature review

Much of the information in this chapter was originally presented at the 1999 CIM workshop (McKenna, 1999). Additional information can be found in Adams (1983), von Oppenfeld and Hiser (1994). Alberta Environment (1985), Hu et al. (1992), Mchaina (2000), and McKenna et al. (2000).

4.4 Successful reclamation

This section describes successful reclamation in three ways: through definition, a list of ideals, and by breaking it down into ten elements.

Defining successful reclamation

Successful reclamation can be measured as it supports the mine during operation, as it applies to landscape performance, and by its endpoint.

Successful reclamation:

- **as measured during operations** means that progressive reclamation and certification occurs throughout the life of a mine, using an open and transparent decision-making process that includes regulators and all stakeholders (local groups and communities affected by decisions and who have an interest in the operation), in a way that attracts and keeps the trust between all three groups throughout the life of a mine so that reclamation supports the major business goals of the mining company.
- **as shown through landscape performance** means that the reclaimed land meets agreed upon land uses, there is reasonable assurance that the land will continue to exhibit good performance and will continue to be an acceptable and useful part of the regional landscape and its ecosystems.
- **as measured against an endpoint** means that transfer of liability for, and custodianship of, reclaimed land is turned over to a willing recipient (usually the state) in an orderly, timely, and economical manner and allows fulfilment of the "temporary use of the land" covenant.

Ideals for successful reclamation

It is a worthwhile exercise to set out an ideal program in support of successful reclamation. While perhaps unachievable in its entirety, it provides a clear and defensible target. Most of the ideals have been achieved individually by one or more of the mines visited – but few mines have achieved more than a couple of these ideals.

This set of ideals would be easier to achieve for a large coal strip mining operation (where land is reclaimed using the major mining equipment and only a small "operating window" of disturbed land is maintained each year) than for an open pit metal mine. The challenge is both necessary and daunting for all mines and the approach would have to be tailored for local conditions.

The ideal program would follow the following path:

1. A comprehensive closure plan is completed prior to start up, is executed over the life of a mine and remains on schedule, on budget, and with no major changes or surprises. The closure plan is fully integrated with the ongoing operation.
2. An effective stakeholder and regulatory consultation process starts before mining, continues beyond custodial transfer, and involves meaningful ongoing dialog with all interested parties.
3. There is a steady level of progressive reclamation, including all aspects of reclamation such as resloping, coversoiling, revegetation, creeks and river establishment, monitoring and maintenance. Low variation in levels and types of annual activities allows a steady and experienced reclamation workforce and consistently level budgets.
4. Land is certified progressively, and after a few start-up years, there are equal amounts of land being disturbed, reclaimed, and certified every year. The work, while still requiring innovation and creativity, becomes a routine part of the mine's annual operating cycle. At closure the last disturbed land is reclaimed and certified promptly.
5. Reclamation is indistinguishable from the operation, with large mining equipment handling much of the reclamation work as part of its normal operation.
6. Research is carried out in advance of mining, or provides just-in-time answers for reclamation activities.
7. Goals are few, achievable, practical, environmentally sound, and sufficient to ensure reasonable landscape performance. The goals of stakeholders, regulators, and miners are coincident and do not change with time.
8. Any long term monitoring or maintenance is planned for and agreed to by all parties and executed in a timely and economic manner.
9. Mechanisms are in place to allow timely and progressive custodial transfer of the land along with residual liability.
10. The resulting landscape is useful and fits into (and supports) the local ecosystems and economy. Changes to the land, in terms of use or properties, are understood and accepted by all.
11. The mine, stakeholders, and regulators earn and keep each other's trust throughout the life of the mine.
12. All parties are accepting and proud of the accomplishments in creating a new landscape.

Mines, regulators, and stakeholders need to find common ground between today's reality and the ideals listed above. Failure to progress towards these ideals will leave the industry and regulators facing the certification barrier, custodial transfer barrier, and liability trap (see Chapter 2) that threaten the viability of the industry in Canada.

Elements of successful reclamation

Traditional reclamation is greening up the landscape in a patchwork quilt-like fashion. Successful reclamation builds on this technical and operational know-how and includes other less technical elements. This section defines ten elements of successful reclamation, and provides a subjective rating of the present performance of the Canadian mining industry. While advanced in technical areas, there is a long way to go to improve the scorecard on other elements. Fortunately, with management attention and dedication, other areas could easily be improved. This section also provides illustrative examples of 10 mines meeting individual elements of successful reclamation. It is meant to show that each of the elements is achievable on its own. Most of the mines described below are doing better than average on the other elements as well.

Management support

Foremost, full support of management, from the mine manager to the chief executive officer, is critical to successful reclamation. Management cannot just pay lip service to this effort – they must be willing to actively support the work, supply the budget and staff and intervene when necessary. At most mines, management feels they give ample support but few reclamation specialists feel they receive sufficient support.

WISMUT GmbH is a large mining company charged with remediating its Cold War uranium mines and mill tailings facilities in eastern Germany (BMWi Federal Ministry of Economics, 1995; Muller, 2000). Once involved only in production, the mine has downsized to 4000 employees whose sole focus is now decommissioning and reclamation – essentially mining in reverse. Management's entire focus is reclaiming the land to a safe and useful state as quickly as practical. Management applies a mining framework and infrastructure to the reclamation work – over C$10 billion is being spent to reclaim the disturbed land. Few mines are as committed or focused on reclamation.

Stakeholder involvement

Meaningful involvement of stakeholders is needed. It takes a great deal of work and integrity to act on the information and preferences of these stakeholders. The assistance of a public consultation expert is useful.

The Olentangy River Wetland Research Park at the Ohio State University is a 12-hectare reclamation research site (Ohio State University. School of Natural Resources, 1995). Stakeholder involvement is critical to ongoing funding and adoption of their research findings. Numerous wetland researchers participated in the design and construction and dozens of graduate students have done their research work on the site and act as ambassadors as they enter their professional careers across the country. Hundreds of school children, community groups, university football players, and even the university president helped to build boardwalks and plant vegetation. The result – hundreds of people all feel pride and ownership in this premier reclamation research site.

Communication

Communication of plans and demonstration of progress to stakeholders is essential. Communication methods (but not the message) must be tailored to the audience – aerial photographs, paintings, three-dimensional models and field trips can be useful tools in communicating existing operations or an end vision. Openness, transparency, and integrity are key. Overselling of ability or outcome is a common trap that must be avoided.

Highland Valley Copper has an extensive communication program for employees, contractors, and stakeholders. Of note is the annual open house, where thousands of members of the public are bussed to the site, take production or environmental tours, receive a free T-shirt, and enter a lotto to catch trophy rainbow trout in a reclaimed tailings pond (Hamagucki, 1999). While glossy brochures, Internet sites, and carefully crafted press releases are important communication plan components, perhaps the greatest influence on stakeholders are field tours (or walking trails) to reclaimed sites for people to judge for themselves the quantity and quality of reclamation.

Planning and design

Good planning and design by multidisciplinary teams of professionals are essential. Mines need to generate realistic closure plans approximately every five years and demonstrate ongoing progressive reclamation that will lead to an orderly closure. Chapters 2 and 3 describe the current state of practice.

Syncrude Canada is one of the largest mines in the world and, having learned from the mine visits presented in this report, has become one of the more advanced in closure planning (McKee and McKenna, 1997). It has developed its third generation closure plan for its Mildred Lake oil sands operation and is starting closure plans for its two other operations. It engages an external panel of eight technical specialists from different fields, several dozen consultants and researchers, has a team of 15 technical experts from across the company that spend 10 to 40 percent of their activities on closure planning, and has recently created a full time landscape design and closure planning core group of specialists. While this effort is more than most mines can afford, the scale and reclamation costs for these operations are large and justify a high level of commitment and effort.

Economics and decision making

Reclamation involves a multitude of decisions and tradeoffs, many of which have significant economic implications to the mine and society. Inclusion, openness, and transparency in decision making is imperative. Reclamation decisions based largely on net-present value economics are generally misleading and are usually poorly received by regulators and stakeholders.

WISMUT, along with many of its uranium mining / decommissioning contemporaries, is among the most advanced in terms of its economics and decision making. Since the reclamation work is state funded, the decisions made are subject to high levels of scrutiny and are set in a clear and transparent framework. Evaluation of mitigative technologies uses well-crafted systems to rate the costs, benefits, and uncertainties of each. The result are decisions that are acceptable to the company, the financiers, the regulators, and the public.

Research and development

Both research and development are important to identify and solve the many reclamation challenges that each mine faces. Results need to be implemented in a timely manner. For complex sites, 10 to 20 percent of the reclamation budget may go into research and development. Because of the need for multiple growing seasons to test soils and vegetation, lead times of five years are often required for research. Formal mechanisms to incorporate the findings from research and development into the operation are often useful.

Mount Polley Mine illustrates how research and development can support closure planning and successful reclamation (Mount Polley Mining Corporation, 2000). This open pit mountain copper mine has a relatively short mine life (12 years start to finish) and was the only mine visited to start with a full closure plan. The closure plan identified both the importance and lack of available organic matter to incorporate into coversoils – a critical element of landscape performance at this mine. An extensive research program involving numerous test plots using biosols (an organic amendment made from treated municipal sewage) is producing results in time to be incorporated into successful reclamation (Mount Polley Public Liaison Committee, 2000). Research programs don't necessarily have to be large or numerous, but they do need to be well developed and focused to provide timely information that helps a mine to solve its reclamation challenges. Often, research is successfully accomplished through formal industry / government / academic partnerships such as Mine Environmental Neutral Drainage program and the Oil Sands Reclamation Research Network.

Technical and operational know-how

Technical and operational know-how is the knowledge and experience of planning and executing reclamation and getting it done efficiently at full scale in the field. Success rates are high. This expertise needs to be applied not just to bulk reclamation but the finer details as well.

Just about all mines have at least one shining example of operational and technical know-how. Transalta's Highvale Mine, a prairie coal strip mining operation, is an outstanding case. Coal spoils are partially recontoured with the large mining draglines, and final resloping to farmland is done with scrapers. Soils are removed from in front of the advancing mine face and placed on the new land to form high-quality agricultural soil. The disturbed area is minimized and land put back to productive farmland within a few years of disturbance. Every year the mine disturbs, reclaims, and certifies about 100 hectares. All aspects of reclamation and certification are incorporated in the day-to-day operation.

Landscape performance

Having performance that meets predefined goals (worked out with input from stakeholders and regulators) is key. Where expectations are suitably modest, the industry is experiencing success for most terrain units (see Chapter 3). Performance is best achieved when all elements of successful reclamation are employed.

The McKinley Mine is a large coal mine in New Mexico. After mining, the land is regraded to rolling topography with small armoured swales to carry water safely across the landscape. The land is being turned back into productive rangeland. Attention to detail, especially hydrology and soils, means that virtually all areas of this large reclaimed landscape appear to be performing well.

Risk management

A full operational risk-management program is key – one that includes design, monitoring, maintenance, and failure investigation. There needs to be viable contingencies in the event performance fails to meet goals. Too often, reclamation is done with no margins for error, only a single line of defence and no allowances for inevitable construction defects.

The historic Canmore Mines site in the Alberta Rockies is being reclaimed to high-end residential use including an expensive resort. A special review board was formed to review stabilization of underground workings that daylighted within the development. The developer, consultants, government regulators, and the public worked together to approve the work and set in place a self-funded insurance program to provide relief should there be future damage from underground workings. Mechanisms were put in place to transfer any residual liability to the crown to make this multi-billion dollar project a reality.

Independent audit

It is important to obtain independent, third-party reviews of reclamation and closure plans and activities to ensure it is meeting the agreed-upon goals and that the mine is on a path to successful reclamation.

There were only three examples of independent audits observed – these had the form of review boards – the Canmore Mines Underground Review Board described above, Island Copper's Mine Development Review Committee, and Syncrude's Land Redevelopment Technical Advisory Panel. McKenna (1998) provides details about Syncrude's Geotechnical Review Board which may also form a useful model. But beyond these few review boards, independent third-part audits of all aspects of reclamation and closure planning have not been adopted anywhere visited.

A scorecard

In a May 1999 workshop (McKenna, 1999), ten reclamation specialists from the Canadian mining industry rated each of the above elements to determine how the industry is doing in terms of achieving successful reclamation. Table 4-1 presents the results. Participants were asked to rate each element as high (H), medium (M), or low (L) performance. High performance means that there are effective systems in place and being used. Medium means that attempts are being made with mixed results. Low means that either there are no systems or the results are poor.

The survey results show that the Canadian mining industry is not achieving successful reclamation. While it enjoys success on the strength of research and development, technical know-how and landscape performance, it is clear that improvement is needed in a number of other areas. This is especially true in an era of ever-moving goal posts and continually increasing expectations. It need not cost more in the field, but a change in the level of design and technical work is needed. The changes require a shift in management focus. Failure to change means the mining industry will continue to struggle in achieving its ultimate reclamation goal of reduced long term liability and return of the land to a willing custodian.

Based on the mine visits (49 had enough information to score – most mines except for the abandoned ones) a "high" rating has been achieved by at least one, and usually many mines, for individual elements showing that each can be accomplished.

The mining industry cannot solve the major issue of the liability trap on its own. But it must help facilitate a societal and governmental shift to allow full transfer of long term liability for well-reclaimed sites. If mines can fully adopt successful reclamation, it will both help the mining industry survive until changes can be made, and also demonstrate its ability to create landscapes acceptable to future custodians.

4.5 Closure planning and reclamation challenges

For mines and regulators, the challenges to reclamation and closure planning are daunting. This section provides a broad overview of the major challenges. Appendix A describes each of 121 challenges that have been identified in greater detail.

Design and planning

The absence of a clear methodology or framework of defining goals and designing to meet these goals is the greatest challenge in design and planning. It is further complicated by the large tracts of disturbed area that are already reclaimed or disturbed in ways that make goals that are change retroactively difficult to achieve. Perhaps the greatest deficiency in the present framework is a method for dealing with the uncertainty of long term landscape performance.

Reclamation operation and construction

Reclamation operation and construction is a relatively mature area and so has overcome most of the earlier challenges. The greatest challenge facing this area is becoming efficient at the finer details of reclamation – finishing up the bulk reclamation with repairs to bare areas, constructing streams, and ensuring the final finishing touches are taken care of. Adopting the dualism of efficient bulk reclamation with careful finishing reclamation is a significant challenge.

Monitoring and maintenance

The challenge of monitoring and maintenance is to initiate a system that can gather and manage the data. This requires a special dedication of a few staff members. Designing a program that collects the right data at the right frequency, then a management system that allows the mine to act on this data is critical. Filling the gap for the lack of historical data or even inputting the historical data into the data management system is often overwhelming.

Financial

Financial challenges are perhaps the greatest faced by mines. Most of these centre around the lack of understanding regarding long term liability. Once this liability is better recognized, the key challenges are to manage reclamation costs throughout the life of a project, to try to avoid escalation of closure costs due to changing regulations, and to set up conditions for the closure period that will permit efficient closure.

Perhaps the most pressing challenge is to address the post-closure dormancy strategy to which so many mines default. There needs to be better management of costs, and financial instruments in the planning for and during the closure period so that the mines have the resources and desire to finish reclaiming their sites.

Cultural

Cultural challenges relating to closure focus around the need to work closely with local stakeholders to understand the goals and desired land uses for the reclaimed sites. The conflict between the goals of regulators, stakeholders and miners needs to be resolved early on, allowing all parties to work closely towards common, clearly understood goals. Even if common ground cannot be found, ongoing dialog about goals can reduce uncertainty and unease.

Ironically, at some mines, one of the mechanisms for poor performance of reclaimed landscapes is abuse by the local community members after closure – theft, vandalism, inappropriate land use, and lack of care and attention. The local community needs to understand their roles and responsibility as users of the landscape to contribute positively to its ongoing performance.

Regulatory

The challenges faced by mines relative to regulatory interaction are considerable and most come down to the lack of clear and achievable goals. Again the solution depends on having a good framework for setting and achieving goals. Attempting to mandate good performance through regulation or prescriptive goals has much less chance of success compared to establishing a few key objectives and working together over the life of a mine to achieve them.

There also needs to be a mechanism to accept moving goal posts. It is naïve to think that regulations, expectations and scientific understanding won't change over the life of a mine, especially in that most mines operate over decades and many over a century. But there also needs to be protection for the mine's investors against ever increasing reclamation requirements and costs.

Physical

Physical performance goals need to be better framed and specific methodologies to achieve them on a technical level need to be both better understood and employed. The most glaring shortcoming is the poor understanding and implementation of surface-water management.

Chemical

Most mines create landscapes that are especially prone to chemical migration and the costs to remediate the reactions and migrations is high. Many mines are struggling with acid rock drainage issues in particular. Better planning from the start can help to reduce costs. Bringing to bear all elements of successful reclamation will be especially important for problem sites.

Biological

Biologic challenges have been addressed and many have been resolved over the past several decades. Major challenges now are moving to more ecosystem-based approaches and the exclusive use of native vegetation required in some jurisdictions. Understanding how successional changes in vegetation and wildlife affect the landscape will remain challenges well into the future.

Land use

The greatest challenge in land use is setting and achieving land use targets in a sustainable manner. The land uses must be chosen carefully and realistically and, once they have been agreed upon, mines need to work hard to achieve them. Depending upon the level of design constraints, many desirable land uses may not be achievable — for many sites, the focus on physical, biological and chemical stability come long before considerations of land use.

Complexity of landscapes

Landscapes are complex systems and are subject to perpetual and extreme internal (intrinsic) and external forces. Prediction of their future behaviour is difficult except perhaps at the broadest, most simplistic level. A full understanding of the intricacies and mechanisms behind dynamic landscape performance is impossible. Even a modest understanding may not be practical.

Miners need to avoid promising that the landscape will perform in certain ways, unless they are willing to control its evolution through long term maintenance. Designers must take steps to understand the basic mechanisms and bring them into their design practices, and chose design practices that are somewhat forgiving of ignorance.

Complexity of mine/regulatory relationships

It is not only the physical landscape that is complex but also the system of goals, regulations, legislation and personal interaction that go into building and judging a landscape.

Steps to simplification are needed. A purely prescriptive approach ignores the reality of landscape complexity and is doomed to provide poor results at all but the simplest of sites. Instead, mechanisms must be created that allow the use of judgement and be accepting of best efforts and the use of elements of adaptive management. Regulatory control needs to be shifted away from meeting prescriptive criteria and providing assurances of long term performance based on complex models, and moved towards creating reasonable designs, having them approved, and following through on these designs in field construction. This new framework bypasses many of the challenges and provides measurable performance goals for the mines and regulators. Mutual trust is a key aspect.

4.6 Novel concepts and innovations

Responding to the myriad of challenges, mines are innovating. Appendix A includes over 100 novel concepts and innovative practices that are summarized below.

Design and planning

Mines are becoming better skilled at developing closure plans and investigating more formal approaches to landscape design.

Reclamation construction

Mines are developing methods for better placement of materials, using one-time placement, and experimenting with direct seeding technologies.

Monitoring and maintenance

Mines are actively developing rational methods for acquiring and storing and communicating data. Off-site automated control of pumps and other monitoring of critical systems is being developed. Use of remote sensing and GIS is being implemented.

Financial

Mines are understanding the high degree of uncertainty in estimating reclamation and closure costs (especially for premature closure) and starting to develop acceptable financial systems for long term maintenance.

Cultural

Mines are experimenting with activities that can make the reclaimed landscape more appealing to stakeholders – through building better, more aesthetically pleasing landscapes and involving stakeholders in decision making and reclamation.

Regulatory

Innovation in this area is focused on either trying to change existing regulatory systems to make them more amenable to successful reclamation or forging new regulatory systems.

Physical stability

Mines are experimenting with methods of increasing physical stability, mostly through managing surface water better.

Chemical stability

Most of the innovations of interest focus on identifying problems and problem materials before mining starts, mainly centred around acid rock drainage.

Biological stability

This has three main areas of focus – refinements of revegetation practices to reduce costs (especially direct seeding trials), innovative methods of creating improved wildlife habitat, and more ecosystem / landscape approaches to vegetative communities.

4.7 Solutions

It is becoming increasingly clear to many mines and regulators around the world that closure planning is a valuable activity. It is also clear, however, that we do not have all the tools to ensure that mines can reliably meet their closure goals. The existing model of greening up static landscapes does not provide the required framework for what are known to be complex dynamic landscape systems.

Clearly, a different level of activity is required in the setting of goals, designing and constructing the landscape, and assessing its performance. Goals cannot be made up nor agreed to without proper consideration of their achievability. The landscape cannot be constructed with the simple instructions of a mine manager standing in the field, nor by considering individual landforms or individual sciences separately. Questions of long term maintenance cannot be left until the landscape is largely constructed. Questions of long term liability need to be settled before mining begins, not after it has ceased.

A more integrated approach is needed – integration of goal setting, design and construction and landscape elements. A framework is required that encompasses each of these items and allows the various specialists to work together to provide designs and landscapes that come with a reasonable assurance of meeting the agreed upon goals economically.

Landscape engineering (Chapter 5) is proposed as an umbrella discipline for creating sustainable landscapes and embracing successful reclamation. It provides an engineering focus to create landscapes that meet specific goals. It also provides a multidisciplinary approach that integrates mine planning, operation and reclamation. In particular, it allows a rational framework for designing landforms and substrates and for selecting vegetation.

To achieve successful reclamation, miners need to build on the successful elements of existing reclamation practice and enhance it with a combined scientific and engineering focus, bringing to bear the tools available to engineers and meshing the skills of the biologists and other scientists. Furthermore, mine staff need to communicate the goals, uncertainties, and costs to mine management and financial community in ways that they can also understand.

Landscape engineering offers a new framework but in itself will not be enough. Mines need to focus on all the elements of successful reclamation and work towards improving their own scorecard and that of the industry as a whole.

But even given improvements in all of these areas, the most daunting of all is the need for a societal change. The general belief that societies can flourish without primary resource industries such as mining will historically be considered as one of the greatest mistakes of the current era (Homer-Dixon, 2000). Society needs to embrace or reaffirm the need for resource industries, and be willing to accept the landscape changes that these bring about. But even more than this, society needs to re-examine how it accepts long term liability of events that are outside its control. We accept that the natural landscape changes, but are unwilling to accept liability for the changes that occur in reclaimed landscape. Until we can resolve the issues of liability and, in particular, methods of limiting long term liability for mines for their activities for which society has benefited and prospered, mining will be unable to fulfil its promise of temporary use of the land, and the mining industry will continue to decline.

When the mining industry has demonstrated and communicated its responsibility for successful reclamation (and environmental impacts in general) perhaps society *will* better recognize the value and importance of mining to local, regional, and national economies and sovereignty. Better institutions for determining, accepting, transferring and limiting liability will eventually emerge out of necessity and regional or international economic advantage. Additional costs for reclamation and closure will only marginally affect commodity prices. The key is to recognize the shortcomings in present systems and start the transition to a more workable system. The challenge is great. This study has focused on the positive and positively challenging aspects – technical, financial, and societal. Chapter 5 on landscape engineering provides a new framework – perhaps a significant step in the transition to where mines will be able to properly fulfil the mantra of temporary use of the land, and create new useful landscapes for society.

4.8 Conclusions

Successful reclamation has been defined as that which supports the mine's operational and corporate objectives, allows reclamation certification and transfer of liability, and can be reasonably assured of providing acceptable long term performance.

Elements of successful reclamation go beyond closure planning, design, and construction to include management support, stakeholder involvement, communication, economics and decision making, research and development, landscape performance, risk management, and independent audit. A scorecard of these elements reveals an even split of low and medium ratings for the Canadian mining industry. But a "high" rating has been achieved by at least one, and usually many, mines for each element showing that each can be accomplished.

Along with the previously described liability trap, lack of fulfilment of these elements means that successful reclamation is not being achieved – many sites are not being fully reclaimed at closure, mines are not returning the land, and mines are not fulfilling the covenant of "temporary use of the land."

Innovative practices, and individual elements of successful reclamation, were noted at most mines, but a broader initiative is needed. Four things have to occur:

- mines need to embrace successful reclamation, integrate closure planning with the mine operations and employ the other elements of successful reclamation by addressing each element formally in their environmental management, supported at all levels within the company
- a framework of landscape engineering needs to be adopted and implemented
- mines need to focus on progressive reclamation and progressive closure and regulators need to encourage and reward this activity
- legislation to allow full transfer of liability for well-reclaimed sites is needed.

A search for a single ideal system or method by which to direct or regulate mines and their reclaimed landscapes will not likely be successful. But such a search provides useful insights and fruitful outcomes that can allow mines, regulators, and stakeholders to define their own elements of successful reclamation. Based on a model of trust, useful and economical landscapes can be created.

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Table 4-1 Canadian reclamation practice scorecard

Reclamation element	Scored by workshop participants	Based on 49 mine visits	Number of mines with "High" rating (N=49)	Comments
Management support	L	M	18	Workers generally feel low levels of management support, but managers feel they are providing high level of support
Stakeholder involvement	L	M	13	A few mines have successful stakeholder programs, many have none
Communication	L	L	12	In general, there is poor communication to staff and stakeholders about reclamation efforts and decisions
Closure planning	M	M	19	Many mines have effective closure planning systems, many have none
Economics and decision making	L	L	7	Few mines have rational methods for deciding the amount and timing of reclamation expenditures
Research and development	M	M	8	Some mines have a lot of useful research, many have none
Operational and technical know-how	H	M	20	Most mine have a good ability to green up large areas, but few are proficient at the finer details
Landscape performance	M	M	5	Landscape performance is generally quite good, but few areas have been tested by extreme events
Risk management	L	L	1	Few mines consider risk or long term performance
Independent audit	L	L	4	Few mines use any auditing system

Chapter 5

Landscape Engineering

5.1 Introduction

Landscape engineering is introduced as a specialized branch of civil engineering aimed primarily at mine reclamation at the landscape scale. It is a composite of the physical, biological, and chemical sciences and engineering disciplines involved in mine reclamation. Landscape engineering addresses the creation of reclaimed landscapes that meet the goals of mining companies (and their regulators) during mine operation and those of society and the new custodian after mine closure.

Though primarily concerned with successful reclamation (see Chapter 4) for the mining industry, landscape engineering has broader applicability to creation of other new landscapes. Examples include landscape-scale civil earthwork projects such as hillslope regrading for municipal development, landfills, and large dams, and linear projects such as pipelines, roads, and canals – any project where performance of a drastically disturbed landscape is important.

Arguing for this new specialized engineering discipline, this chapter defines landscape engineering and compares and contrasts it with similar disciplines. It describes the current state of mine reclamation practice, the need for a more formal approach, and identifies elements of landscape engineering. The chapter goes on to discuss its past and its potential future evolution, and describes how it is starting to be applied to support successful reclamation for the mining industry.

A note on terminology – while this chapter identifies this systematic approach to landscape creation as “landscape engineering” there is widespread resistance to the use of the word “engineering.” Most reclamation is done by reclamation specialists, who are often biologists and who are justifiably proud of their efforts. These same people see that engineers create most of the challenges they face – to many, the notion that more engineering will improve the situation is counterintuitive at best. This chapter attempts to bring some unification to the work of these various specialists. It uses the proper term "landscape engineering" and attempts to make the case that it is well described in an engineering framework. Nonetheless, the less-accurate term "landscape design" may be easier to sell and be more inclusive of those specialists who are not engineers – and indeed, non-engineering specialists will usually outnumber engineers on the team.

5.2 The need

Mining drastically disturbs the landscape. The ecosystems, substrates, and indeed the parent rock are removed and transported kilometres away, the mineral wealth is liberated, new materials such as tailings and waste rock are deposited. Large excavations and other new landforms remain. All biochemogeophyscial cycles are reset. The landscape is new.

For millennia, and until about 30 years ago, miners simply walked away from the site after the wealth was exploited (Cummins and Given, 1973). Behind them, they left devastation – landscapes replete with chemical and physical hazards, causing pollution downstream and downwind, and the landscape itself made useless by mining (United States Department of the Interior, 1967), often impacting on human health and safety. The extent of the devastation was often viewed as a monument to society's domination over nature (especially by miners).

Public outrage at the mining's environmental legacy eventually required that the mining industry adopt a new strategy — minesites needed to be reclaimed. After stiff initial resistance, the industry eventually embraced better environmental practices (including reclamation) and billed mining as a "temporary use of the land." Slowly, over two decades, state by state and province by province, the change became complete. Mining permits would no longer be issued unless the mining company promised to reclaim the mine landscape, removing the hazards and restoring its usefulness.

Starting in the 1970s, mine reclamation focussed on greening-up the land in a patchwork quilt-like fashion. Infrastructure such as buildings was removed, slopes regraded and coversoil placed, and agronomic grasses planted. Mines expected to be able to walk away from their reclaimed sites.

This reclamation usually did not restore the landscape to predisturbance conditions. The reclaimed landscape was fragile – susceptible to gullying and erosion and degradation of performance under modest climatic events and other disturbances. Some landscapes produce acids and metals that can severely affected fish and plants, and include physical reminders of mining such as highwalls, tailings ponds, and roads.

The public remained disappointed in the results. Various changes in reclamation requirements occurred, some demanded by regulators, some offered by industry in return for mining permits. Landscapes were designed to have lower rates of erosion (through the use of planar slopes and terraces on dams and dumps), channels were dug to re-establish creeks and rivers, some jurisdictions required restoration of approximate original contours, others required planting of certain vegetation types. The desire to restore original land uses, such as agriculture or forest, came as a new requirement while progressive reclamation became a universal requirement. Mining companies, both optimistic and faced with no alternative, agreed to these conditions.

Even with these new agreements, many mines were still being abandoned, largely unreclaimed. The land was reverting to the state, and either public monies were used to stabilize or reclaim the sites, or the sites simply were added to the inventory of abandoned mines. In the 1980s and 1990s, requirements for closure planning and financial assurance (often in the form of bonding) became a requirement in an effort to help ensure that the sites would be reclaimed as promised, and to provide assurance that the public purse would be protected.

A recent survey of closure planning, landscape design, and landscape performance, has identified that despite the best intentions, high investments, and considerable improvement in technology, mining is still a one-time use of the land (Chapter 2). Uncertainties over long term performance and liability means that mines are not turning over reclaimed land to the original owner, but instead are hanging onto the mines indefinitely, with no prospects for certification or custodial transfer. Public acceptance of the present state is unlikely to persist. The viability of the industry is threatened.

Over the past thirty years, reclamation science and practice has grown considerably. But it has developed in an ad hoc way, perhaps as much art as science. The artisan/craftsman phase of reclamation has produced a wide variety of technologies, and been achieved reclamation of hundreds of thousands of hectares. But, lacking a formal framework to establish and reliably meet goals and discharge liabilities, it generally fails to produce successful reclamation (Chapter 4).

Technological disciplines like reclamation go through a predictable evolution, and reclamation seems primed to take the next step, to an era where there is a framework for defining goals, and methods to reliably meet these goals. It is ready to move from the craftsman stage, into an early, largely empirical and semi-quantitative engineering stage that builds on the successes of the past. More clearly stated, mine reclamation has reached a stage where the present paradigm of reclaiming the landscape using artisan methods no longer satisfies mining companies, their regulators and stakeholders, or the financial community. A new more thorough, systematic approach for goal setting and meeting those goals is needed.

5.3 Defining landscape engineering

This section explores the definition of landscape, of engineering, and attempts to carve out the role of landscape engineering. It is compared and contrasted with different kind of engineering and reclamation. It discusses the three main aspects of landscape engineering – closure planning, landscape design to meet goals, and the specific unifying technologies of landscape engineering – the prediction and design for fluxes and risk management – cornerstones of this work.

Reclamation can be defined as the process of creating useful landscapes that meet a variety of goals, typically creating productive ecosystems (or sometimes industrial or municipal land) from mined land, but also applied to production of new lands (for example, dredging and dyking of shoreline). It includes all aspects of this work including material placement, stabilizing, capping, regrading, placing coversoils, revegetation, and maintenance.

Landscape is broadly defined by the Oxford English Dictionary (second edition) as "a view or prospect of natural inland scenery, such as can be taken in at a glance from one point of view; a piece of country scenery" or "a tract of land with its distinguishing characteristics and features, especially considered as a product of modifying or shaping processes and agents (usually natural).” It is typically the size of one or more small watersheds, typically in the range of tens to thousands of hectares. More than land, it includes rivers, creeks, lakes, and sometimes even the ocean. It is focussed on the earth’s surface, but recognizes the importance of substrate especially to groundwater hydrology and soil. It includes the adjacent undisturbed areas as it must honour the processes and continuity in the surrounding landscape which may be natural, disturbed, or scheduled for future disturbance.

While there are many good definitions of engineering, the one provided by the Accreditation Board for Engineering and Technology (of Baltimore, MD) is particularly useful here: “Engineering is the profession in which a knowledge of the mathematical and natural sciences, gained by study, experience, and practice, is applied with judgement to develop ways to utilize, economically, the materials and forces of nature for the benefit of mankind.”

Narrowly then, landscape engineering is the application of mathematics and science to create useful landscapes. Both more broadly and specifically, landscape engineering is the interdisciplinary application of engineering and other applied sciences to the design and creation of anthropogenic landscapes. It differs from, but embraces traditional reclamation. It includes scientific disciplines: botany, ecology, forestry, geology, geochemistry, hydrogeology, and wildlife biology. It also draws upon applied sciences: engineering geomorphology, landscape architecture, and mining, geotechnical, and civil engineering.

Landscape engineering builds on the engineering strengths of declaring goals, determining initial conditions, iteratively designing, predicting performance based on knowledge of the design, monitoring performance, and adjusting designs to meet the declared goals. It builds on the strengths and history of reclamation practice. Its distinguishing feature is the marriage of landforms, substrates, and vegetation throughout all phases of design and construction, which previously have been kept as separate disciplines.

Landscape engineering will be central to addressing the physical and chemical stability of anthropogenic landforms over specified timeframes, or to design and construct landscapes so that the rates of physical and chemical degradation are in keeping with the declared goals (and indeed will be integral in the setting and refining of these goals).

Though landscape engineering embodies all elements of traditional engineering (planning, investigation, design, construction, operation, assessment, research, management, and training), it is focussed on three main areas. The first is *closure planning* – which includes goal setting and design of the landscape as a whole. The second division is *landscape design* more focussed on the design of individual landforms to reliably meet the goals as set out in the closure planning process. *Landscape performance assessment* is critical to both of these, and is also important for estimating liability and levels of financial assurance. The iterative process of planning, design, and performance assessment by a multidisciplinary team is the basis of landscape engineering.

Much of landscape engineering's focus is on the top few metres of the landscape – areas where most of the landscape performance is concentrated, where changes can be made economically, and where the greatest interaction of the ecosystem, the substrate, and the water occurs. But they will also influence the initial siting and methods of placement of the materials in the landscape.

In particular, landscape engineering sets out a new framework a new set of tools, new methodologies, new philosophies, and more transparency in design and communication. It declares these methods and philosophies up front, and set goals that are measurable and achievable. It is the discipline charged with achieving successful reclamation.

The team of specialists

In contrast to a multidisciplinary field like oceanography, which is collection of scientists from different independent disciplines who each study the ocean (Bascom, 1988), landscape engineering can only be adequately performed by a team working together. Oddly enough, it may be erroneous to suppose that any one person can be a "landscape engineer." It is the work of the interdisciplinary landscape engineering team that defines the work. Perhaps the most similar interdisciplinary analog is coastal engineering (see United States Army Corps of Engineers, 1984) that unites several disciplines and whose unifying technologies include wave mechanics and prediction, coastal processes and rates, and simulations to estimate effectiveness of artificial works. River engineering (Petersen, 1986) done well is also a good analog.

The following disciplines are represented in the core team.

Mine planning

The design of the mine, including excavations, roads, dams, and fills, is done by a mine planner who forms a core member of the team. Mine planning involves material excavation, hauling, placement, schedules and budgets. Presently, mine planning is little constrained by landscape elements other than geotechnical. Most mine planners are experts at optimizing plans given a large variety of competing objectives and constraints.

Reclamation specialist

Reclamation specialists are those who have formal training or extensive experience in mine reclamation. They bring practical experience of getting the job done, help to co-ordinate the group, and bring the broadest breadth of understanding of reclamation and environmental matters to the team. They are most often the best versed in regulatory requirements. By virtue of their formal training, most will also fill the role of one of the other specialists on the team.

Geotechnical

Geotechnical aspects of landscape design are relatively mature compared to other areas. The focus is on providing landforms with that have good stability and that subsidence does not significantly impact on long term performance.

Groundwater

Groundwater aspects within a dump or tailings pond are generally handled by geotechnical engineers or hydrogeologists who take care of the seepage as it relates to stability (slope stability and piping). Though often highly mineralized, groundwater quality within the new landforms is not usually regulated and therefore is seldom a concern. Groundwater quality outside the footprint is subject to high levels of scrutiny by hydrogeologists. Soil moisture, where studied, usually falls to soil scientists, but is sometimes dealt with by those who study unsaturated soil mechanics, especially for engineered covers.

Presently there is an inadequate linkage between seepage, groundwater quality, and soil moisture. This is one of the key areas for landscape engineering to focus because they are so closely related by water and chemical balances and fates, and small changes in design of these elements can have dramatic impacts on landscape performance.

Surface-water hydrology

The surface-water hydrologist is responsible for getting the water safety from the landforms to the on-site drainage and designing the on-site watercourses to safely convey the water to receiving systems. Overland flow, watershed design, topographic design, and river, creek, and lake design are common activities. Wetland designs and design for fish habitat are often needed.

Present performance in this area is low, a special concern since the water is the lifeblood (or as some would say, the septic system) of the landscape, is critical to many land uses, and also presents a major unzippering mechanism for landscape performance. This area especially needs integration by all members of the team.

Soils

Soils are among the most critical elements of achieving good landscape performance. It would seem that reasonably good performance has been achieved to date at many mines with only modest technical input from soil scientists. The design of coversoils and placement techniques is an interdisciplinary effort that can provide large payoffs in performance and cost. The design of coversoils is probably the single most important aspect of landscape design because it affects vegetation performance, surface-water hydrology, groundwater hydrology, and ultimately land use.

Vegetation

The type of vegetation specialist involved will depend upon the regional ecology and the anticipated land uses. Often foresters or agronomists are involved, and increasingly botanists, landscape ecologists, and other reclamation specialists. Trends are moving from solely achieving erosional stability through the use of lush agronomic ground covers towards kick-starting ecosystems at the landscaped level.

Fish and Wildlife

Fish and wildlife are key indicators of good landscape performance for most regulators and stakeholders and deserve more technical attention in reclaimed landscapes. Creation of permanent fish and wildlife habitat within new landscapes is an especially immature area of landscape engineering, but one demanded in most regulatory frameworks.

Traditional environmental knowledge

Local inhabitants, especially First Nations Peoples, often possess traditional environmental knowledge, often as an oral history and personal knowledge (Johnson, 1992). Only very modest gains have been made in this area.

Other

Every mine is unique and has unique challenges. Mines will often require one or two more specialists to participate on the landscape engineering team. Sometimes these specialists will consult to the team. For example, geochemists may be required to provide understanding and control of geochemical reactions. Geotechnical engineers specialising in unsaturated soil mechanics may be required to provide cover designs for acid producing dumps. Nuclear physicists or environmental risk assessment specialists may be needed at sites where there are concerns about radioactivity. Where fish and wildlife are special concerns, an expert familiar with very specific aspects of certain species may be useful. Design of lakes and wetlands is a specialty that may be beyond the staff hydrologist. The vegetation expert may require assistance in forestry, ecosystems, landscape ecology. If long term landform evolution is important, a geologist or geomorphologist may be required. A seismologist may be required for seismically active areas. If the site has historic value, a historian or historical preservation specialist may be needed. A regulatory and stakeholder consultation experts may be a valuable addition or trainer for the team.

Table 5-1 provides a list of present performance of the various disciplines involved in landscape engineering with respect to successful reclamation. Areas needing improvement won't come just from the discipline named, but from the team as a whole.

Typical activities of a landscape engineering team

Landscape engineering can be further illuminated by its activities and responsibilities. The team may perform the following work:

- participate in a closure planning and reclamation team
- guide goal setting, preparation of environmental impact statements
- guide ongoing stakeholder consultation programs
- develop an evolving series of closure plans, from initial conceptual ones, to final decommissioning plans
- instigate baseline monitoring and assessment programs
- develop research and monitoring plans to answer outstanding questions from closure planning

- provide overall design guidance for the landscape, landforms, and specific elements of the landscape
- monitor and guide construction and reclamation activities
- assess landscape performance against agreed upon goals
- provide management of the overall process
- aid in the training of others

A framework for landscape engineering

Landscape engineering often works in the following design cycle:

- Quantification and understanding of pre-disturbance conditions and conditions in the similar or adjacent natural and anthropogenic landscapes
- Declaration of goals
- Postulation of a landscape design that includes methods of disturbance, material transport, creation of new landforms, and reclamation
- Prediction of the performance of the landscape under the new design
- Iteration of the goals, understanding of the landscape, design and prediction
- Seeking regulatory and stakeholder approval
- Construction and ongoing monitoring (using elements of the observational method and adaptive management)
- Changes to the sequence for existing and newer anthropogenic landforms
- Monitoring and maintenance of reclaimed landscapes
- Facilitation of custodial and liability transfer to a new custodian

This process will occur at the terrain unit, landform, and landscape scale, beginning before a mine starts and finishing after it is closed.

Other distinguishing features

People involved in landscape engineering will often be both specialists and generalists, and will come from a variety of backgrounds. Learning to work together effectively is a skill that each member, and the team as a whole, needs to develop.

Landscape engineering is for large areas. Typically the smallest areas would be at the landform scale – tens of hectares to tens of thousands of hectares for large disturbances, and the areas will usually involve one or more small watersheds. Landscape engineering is not as applicable for small areas such as well sites, reaches of small creeks, etc though elements of landscape engineering are useful for these works too.

Unlike science, which seeks to provide *understanding*, engineering seeks to provide *performance*, usually in the face of incomplete data. Unlike say mechanical engineering which specifies materials for manufacturing with known and favourable properties, landscape engineering is more like geotechnical engineering that requires the use of geomaterials with complicated and poorly understood behaviour, many of which will be unavoidably poor construction materials. Landscape engineering, unlike traditional geomorphology, deals with the stratigraphy of artificial and natural materials, and has some influence over the placement of artificial fills and modification of natural materials, and is perhaps closer to applied geomorphology in this regard.

Perhaps the greatest challenge facing the landscape engineering team (and hence one of its defining characteristics) is balancing goals which may be unsuitable or conflicting. The team will also have to balance what can be achieved practically using available equipment and materials (short term costs) with long term benefits and liabilities. More than just design, this landscape engineering team will build and maintain these new landscapes.

Another challenge is to provide estimates of reliability and longevity of the landforms to meet the stated goals. Unlike virtually all other engineering disciplines, the timeframes for landscape engineering performance are often unbounded, and that geomorphic change, perhaps in perpetuity, must be considered. Moreover, the goals may change during this timeframe.

Table 5-2 compares landscape engineering to other related disciplines and Table 5-3 compares it to civil engineering – its closest related engineering discipline.

The design focus of landscape engineering

The technical focus is the detailed quantitative and qualitative analysis and design, with a focus on ensuring adequate landscape performance and predicting long term performance. In this regard, landscape engineering is largely focussed on predicting fluxes, for example, of water, soil, solutes, wildlife, and aspects of end land use such as vegetation productivity. The work culminates with assessing, predicting, and ultimately managing landscape performance. None of these activities in straightforward. These three elements of landscape engineering are discussed in detail below.

More than keeping performance or landscape elements (such as water tables) simply above or below certain thresholds (as is common in geotechnical engineering), landscape engineering is more concerned about predicting and controlling fluxes, often with upper and lower bounds, and often spatially and temporally. Chapters 6 and 7 provide examples of dealing with the uncertainty in estimating fluxes for reclaimed landscapes.

A paragraph on coastal engineering from the Shore Protection Manual sums up the design method for that discipline nicely. The parallels with landscape engineering seem clear:

> "*Because the nature and complexity of most coastal problems vary widely with location, the proper solution of any specific problem requires a systematic and thorough study. The first requisite for such as study is a clear definition of the problem, the causes, and the objectives to be met by the solution. Ordinarily, there will be more than one method of achieving the immediate objectives. Therefore, the immediate and long term effects of each method should be studied, not only within the problem area, but also in adjacent shore areas. All physical and environmental effects, advantageous and detrimental, should be considered in comparing the overall cost, including annual maintenance, and benefits.*"
>
> (US Army Corps of Engineers, 1984)

5.4 Current state of practice

Chapters 2 and 3 outline the current state of practice in closure planning and landscape design and the resulting closure and landscape performance based on visits to 69 North American mines. While many of the results were encouraging, and despite high levels of planning, billions of dollars spent on reclamation, and numerous examples of good landscape performance, today's reclamation is ultimately unsuccessful.

Two step changes are needed. A legal mechanism for transferring liability for well-reclaimed sites back to the state (or original owner) is required so that successful reclamation is rewarded financially (and thus encouraged) and so that mining companies can remove liabilities from their balance sheet and thus remain viable in the long term. This is a societal change largely outside the control of a mining company. The second is a paradigm shift in mine reclamation from being a separate activity from mining to one that is integral and from being an artisan approach to more of more formal engineering – but multidisciplinary. This second shift is within a mine's control and has the benefits of having already started, and its full realization being inevitable.

A review of landscape planning, design, and landscape practice noted considerable success at mine reclamation in the absence of a formal landscape engineering approach. As expectations increase, and sites become larger and more complex, the present approaches are even less likely to be sufficient.

The study highlighted a number of deficiencies and particular areas where landscape engineering needs to concentrate – specifically in the areas of planning, design, and performance.

Planning deficiencies

- Single focus: most reclaimed landscapes are designed by a single person with a focus on a single element of reclamation – often revegetation. A more multidisciplinary focus is needed.
- Goal setting: Most mines have specific goals for their landscape, but these are set by single individuals, and are not necessarily the goals of the regulators or other stakeholders. Furthermore, many of the desired goals are unachievable or unmeasurable. A framework for establishing reasonable goals is required.
- Too much optimism – not enough realism: Closure plans and environmental impact statements are often dominated by overly optimistic predictions of landscape performance. We need to have a more realistic approach, erring on the side of caution. The uncertainties and risks need to be identified and communicated.
- Liability overlooked — perhaps the most important reason to attempt to achieve successful reclamation, liability reduction is generally overlooked in traditional reclamation.
- Certification and custodial transfer barrier — closure planning has been generally unsuccessful in overcoming the certification and custodial transfer barrier. Current techniques create landscapes that are not being certified and are not being transferred back to the crown or an equivalent landowner.

Design deficiencies

- Lack of design: In most cases, there is a near lack of landscape design. The landforms left behind by mining are regraded, topsoiled, and vegetated to agronomic species with little consideration of other goals or design issues.
- Surface-water hydrology ignored: most mines ignore surface-water hydrology in their landscape designs.
- Groundwater tables ignored: aspects of groundwater table, soil moisture, and evapoconcentration at the location of seeps is ignored in most landscape design.
- Lack of integrated team: one or two environmental specialists do landscape designs.
- Lack of predictability and reliability: little thought is given to long term performance of most reclaimed landscapes.

Performance deficiencies

- Streams and overland flow: the lack of engineering and construction of drainage ways results in high rates of erosion during modest hydrologic events.
- Downstream tailing slopes: owing to their fragility and poor soils, downstream faces of tailings dams (in particular, those constructed of tailings) are extremely difficult to reclaim and there are few successful examples.
- Soft tailings: mine staff are surprised at the end of the day at the huge costs of capping and reclaiming soft tailings. These areas also have poor end land use qualities.
- End pit lake filling: it seems to be nearly impossible to accurately predict the rate and final elevation of infilling of mined-out pits by water.

Landscape engineering offers to help in these specific deficiencies by offering a more complete framework for closure planning, landscape design, and performance (and risk) assessment. Perhaps as important to the multidisciplinary approach is simply a thorough and disciplined approach to planning, design, and construction, with a similar attitude and attention to detail as is presently applied to mining geotechnique at many mines.

5.5 Elements of landscape engineering

This section describes landscape engineering based on elements basic to all engineering disciplines.

Planning

Landscape engineering is central to the process of closure planning for landscapes. This work includes public consultation, setting of goals, declarations of design and operational philosophy, risk assessment and communication.

The current state of closure planning is featured in Chapter 2. Closure planning is well advanced, being practiced at most operating mines, but integration with the operations is wanting.

Investigation

Investigation in landscape engineering is analogous to geotechnical site investigations, but continues throughout the life of the project and is of course multidisciplinary. Of interest are baseline monitoring, material properties, geochemical properties, predisturbance site conditions, climatic conditions, streamflows, adjacent environmental conditions, and seismic settings.

Aspects of this activity are well handled as part of developing baseline information for environmental impact assessments prior to permitting of a new mine. Unfortunately, much of this monitoring ceases upon the start of operation and the information shelved until near closure. The work needs to be ongoing and comprehensive (Robertson, 1996).

Design

The landscape engineer will work closely in multidisciplinary teams, working to design the landscape and landforms to meet the stated goals.

The current state of practice for landscape design is featured in Chapter 2. The landscape design is done in a largely artisan approach, with little co-operation among disciplines.

Construction

The landscape engineer will be involved in guiding and observing construction processes, both the construction of the underlying landform and its reclamation, modifying plans and practices as new information becomes available.

Construction of the landform largely involves mine placement of the substrates (dumps, tailings dams, ponds) and its reclamation (regrading / coversoiling / revegetation). Practices are relatively advanced, but finer details such as hydrology need more attention in construction.

Operation

The operation of a landscape largely involves monitoring and maintenance to allow the landscape to continue to meet goals both during mine operations and well into the future.

Most mines consider that the construction phase (reclamation) ends the activity by the mine upon the land, though it is becoming apparent that most mines may require some form of long term monitoring and maintenance to achieve their stated goals. This aspect is evolving rapidly.

Assessment

Assessment includes operational risk assessment during design and construction or assessment of the reclaimed landscape construction or performance to ensure that it has met the agreed-upon goals. Assessment is carried out at four stages.

During the permitting, the environmental impact statement is an estimate of how the final landscape will perform. Given the vagaries of landscape design and construction, this can only be the crudest estimate, though it is generally taken to be a contract for future performance. During landscape design, assessment is part of the ongoing iterative design process and forms the basis of acceptance of plans. During operation, assessment activities include ongoing monitoring, regulatory inspections, and formal evaluations as part of adaptive management. At certification, there is a detailed assessment of landscape performance against agreed upon goals, and prior to initiating any long term maintenance.

Research

The landscape engineering team will conduct or guide research to gain understanding in processes or materials that affect the design or future performance.

Research and development is an advanced topic for mine reclamation, but there needs to be a focus on figuring out the right reclamation and structuring it to provide timely results so that they can be incorporated into the day to day work.

Management

Informed management is required at several levels. The processes of landscape engineering and successful reclamation require management, as does the multidisciplinary team and the landscape itself.

Training

Training will be a critical and ongoing aspect of landscape engineering (especially being a new discipline). Training and experience of working in multidisciplinary teams is critical – especially the understanding of other disciplines needs, outlooks, and frameworks, and in working in a team environment. Planners and management outside the team will require training in the use and functioning of landscape engineering.

5.6 Unifying technologies

Landscape engineering involves more than a collection of specialists, it shares a number of tools and products that require a team of specialists to create. Some of these unifying technologies – those that use several of all of the disciplines – are described below. The models / frameworks are of two general sorts – flux and risk management.

Flux models

Predicting and controlling landscape fluxes is the distinguishing feature of landscape engineering. Landscape engineering will require more than keeping landscape performance or a landscape component simply below or above certain thresholds – as is common in geotechnical engineering. It is often concerned about predicting and controlling fluxes, often with upper *and* lower bounds, and often spatially and temporally. Fluxes of water, solids, nutrients and solutes in, through, and from reclaimed landscapes are typical concerns.

For example, a geotechnical engineer may ensure that the water table in a dam will be no higher than a certain location through the generous use of internal filters and drains. The landscape engineering team may design the water table in a landform that meets more criteria – to be high enough to provide moisture for plants, but low enough to ensure geotechnical stability of the slope, to prevent salinization of the soil, and ensure trafficability of the substrate for certain times of the year. The water table may be allowed temporary excursions into the root zone and may be designed to be closer to the surface in some areas than others to provide a diversity of moisture conditions. Contributions of groundwater flow from the landform to baseflow of a creek may be required to remain within certain limits. This performance must consider long term changes in soil properties, water quality, and vegetative cover, and continue to meet goals without long term human intervention. This level of design is much more complex than traditional geotechnical water table control (Evans et al., 1992). It may not be possible to reliably meet all desired outcomes simultaneously.

Water balance model

As described above, one of the main models that will be employed in landscape engineering is a water balance model (e.g., Ferguson et al., 1985a; Ferguson et al., 1985b; Khire et al., 1997). At the landscape scale, this balance will often focus on surface water. At the landform level, it will also have a groundwater / soil moisture focus. Depending upon the design object, any of groundwater, unsaturated zone hydrology, lake hydrology, and surface-water hydrology may be used. It will often be linked with an ionic or groundwater contamination model. A coupled geochemical model may also be required. It will be applied to cover design, soil design, predictions of long term groundwater tables, runoff models, stream flow models, lake models. Assessment of minimum, maximum, and typical flows will often be required. Controls to limit or promote evaporation, infiltration, storage, percolation, and runoff may be important.

Ionic balance model

Tracking solute concentrations or fluxes within groundwater and surface water will be required. Various balances such as salt balances (Sivapalan et al., 1996), acid-base accounting (for sites with acid rock drainage concerns) or contaminant plume migration may be required. Tracking of ionic movement in the subsurface, in streams, and in lakes may be required, as well as and predicting rates and times of these events.

Landform grading

The landscape should be broken into micro-watersheds to control surface water, limit erosion, and provide topographic (and hence landscape) diversity. Landform grading (creation of swale and ridge topography for control of surface water), adapted for use at the landscape level, should be employed (Schor and Gray, 1995).

Tailored planting

Most landscape goals include re-establishing ecosystems, and also use of plants to meet specific, often short term goals (like groundcover). The use of a tailored planting scheme where species are chosen to kick start ecosystem or fulfil more physical goals is an important tool and will be used at all sites. Accurate predictions of long term soil moisture conditions is critical to successful planting schemes.

Erosion rate prediction

Given that the landscape will erode and evolve, prediction of rates and resulting performance changes may be required. Models to predict these rates will be employed at the landform level, and perhaps even the landscape level (Schumm and Hadley, 1961; Evans, 2000; Hancock et al., 2000). Chapter 7 explores predictions of erosion rates and methods of landform and landscape design to accommodate inevitable erosion and uncertainties in prediction..

Subsurface drainage

Given the need to control the location of the water table (and pore-water pressures) in some structures, subsurface drainage (including seepage control underdrains, blankets, finger drains, and pipe and ditch networks) will usually be employed (see ASCE, 1998).

Natural and artificial analogs

A common activity of the landscape team will be to approximate natural analogs (Keys et al., 1995). Because understanding of natural systems will never be complete, one may be able to imperfectly approximate naturally occurring systems to provide similar performance. Examples from the oil sands region include comparison of nearby dunes and tailings sand, natural lake shore protection, watercourse armouring, soil profiles, and ecosite patch sizes. Artificial analogs may also be used – designing with similar parameters to existing artificial landforms with good performance in the region. Spatially, one may wish to create diversity that is within the range of natural variation (Schneider, 1997) – for example designing with the range of natural variability in patch size, leading vegetation species, and age distributions to provide good wildlife habitat and ecological succession. Use of such analogs requires a reasonable understanding of their important elements.

Risk management

The second hallmark of landscape engineering is the use of a risk management framework. Landscape performance will vary spatially, temporarily, and according to the scale of interest. Many of the important inputs also have spatial and temporal attributes – for example, precipitation, soil composition, permeability, seismic events, and floods. Landscape performance is especially sensitive to thresholds (e.g., Coates and Vitek, 1980b; Coates and Vitek, 1980a; Dietrich et al., 1992) and the probability and distribution of this performance can only be predicted statistically.

Reliability (how closely actual performance matches predicted performance) is a key to landscape engineering. But our ability to predict future performance and provide reliable designs is presently, and perhaps will always be limited. As a result, in many cases, long term maintenance (a form of Bayesian updating) may be required to raise reliability high enough to be acceptable.

Several risk management tools are important to landscape engineering – part of the unifying technologies that help to define this discipline.

Risk Assessment

Guiding design and assessing future performance will require hazard identification and risk assessment. Use of a failure modes and effects analysis (FMEA) is a critical element of this work and will be employed at the landform and landscape level. A list of 162 hazards and other landscape changes is provided in Appendix B to guide this work. Risk acceptance criteria can be developed internally and with regulators and stakeholders.

Minimum critical specifications and checklists

Mine regulations often contain hundreds of goals and requirements for the landscape, some mutually exclusive, some leading to poor performance. Instead a shorter list of minimum critical specifications – performance objectives and indicators, can be developed and applied to landscape design and assessment and forms a checklist for design for construction, certification, and long term timeframes (McKenna et al., 2000).

Reclamation economics

Most mines operate under discount cash flow / net present value analyses for short term decision making. Under typical assumptions, this indicates delays to reclamation activities and striving for minimal specifications. A framework for reclamation economics has been developed by some companies that better values the benefits for the company and understands the cost of carrying liability forward. This type of activity is important for the team in deciding the amount and timing of discretionary reclamation expenditures. Some elements of environmental economics (Bromley, 1995) have application in landscape engineering.

Remaining within precedence

There is a large body of successful designs for most engineering fields, and the level of confidence of new designs that remain within this envelope of precedence is usually high. Landscape engineers need to recognize when their designs are within precedence, and when they are outside this envelope. When civil engineering designers move beyond precedence, for example when designing a new kind of bridge, the tallest building, or a dam made from unusual materials, risks are significantly greater and additional conservatism in design is employed. Many aspects of mine reclamation are beyond precedence, some due to scale, some due to local conditions or materials, some due to changes in technology, others due to the uniqueness of agreed upon goals.

When landscape designs are outside of precedence, conservative strategies should be employed. These include using familiar engineering strategies of multiple lines of defence, erring on the side of caution or using a factor of safety, creation of self-healing or easily repairable systems, and planning a period of monitoring and maintenance. Designing using natural analogs is one strategy to attempt to use precedents from natural systems. Over time, more designs will remain within precedence and confidence will increase. The use of forensics on reclamation failures and publication of the technical details of successes and failures will aid this transition as it has for civil engineering (e.g., Petroski, 1994).

Decision analyses

In most cases, choices for reclamation or mitigative technologies will include tradeoffs of performance, cost, risk, and other desirable elements of the landscape. Methods to make rational, transparent decisions, often in the face of uncertainty, often with the participation of stakeholders are critical. Methods of decision analysis include relative rankings, Kepner-Tregoe weighted decision analysis (Kepner-Tregoe Inc, 1977), and multiple accounts analysis (Robertson and Shaw, 1999). Documentation and periodic re-evaluation of decisions is critical.

Pilots and prototypes

In adoption of any new technology, pilot programs and full-scale prototyping are useful elements to prove concepts, make new learning, and scale findings to the field to reduce implementation risks. Trial plots are common examples of reclamation pilots. Careful application and monitoring of a new reclamation method at the terrain unit level is an example of a prototype.

Long term monitoring and maintenance

As mentioned above, one of the greatest risk reduction mechanisms is long term monitoring and maintenance that uses minimal but careful and diligent monitoring to observe long term landscape performance to determine areas needing maintenance, and those practices that need to be changed (a form of adaptive management).

Declarations

Much of the expected reclamation performance is implicit – and subject to differing interpretations by mines and their regulators. A simple but vital tool is to declare expectations. For example, will the landscape require post-closure maintenance and if so, how much, how often, by whom, paid for by whom? What level of external forces (e.g., earthquakes) will the landscape be designed to withstand without significant change and what will happen upon exceedence? Which vegetation species will be planted versus which are expected to invade (and how long might this take to occur)? These and other declarations, perhaps forming a standard suite, will be critical in communicating the level of effort and the expectations of all parties.

Bonding

Both the mine, the regulators, and the stakeholders are exposed to a variety of risks due to uncertainties in landscape performance and performance of the mine at closure (Chapter 2). A common risk reduction mechanism is financial assurance, usually in the form of reclamation bonding. Should there be poor performance on the part of the mine or landscapes, there is a cache of money that can be applied to mitigate the problems. Ongoing determination of risk and bonding, and methods to reduce a mine's liability will be a significant activity for the landscape engineering team.

5.7 Adoption and evolution

Engineering specialities follow a predictable path through several phases. Landscape engineering will likely follow the same path. Disciplines start as artisan work – limited in results, mostly trial and error, a phase that may last thousands of years, or mere decades. The next phase starts when there is development of an empirical framework. Use of this empirical framework marks the migration to an engineering activity. Next comes the application of mathematical framework as the engineering aspect of the work is solidified. Eventually the discipline comes into widespread use, often following publication of an understandable and comprehensive manual. It becomes regulated as a professional activity. Inexpensive commercially computer codes then become available. Table 5-4 tracks development of several fields that followed this path.

Landscape engineering has been practiced under the auspices of mineland reclamation since the late 1960s and early 1970s. The 1980s saw the start of empirical bases for the work – adoption of benches to control erosion, greening up of large tracks of land using various vegetation technologies. A framework for this work, including some qualitative analysis, is emerging presently, hopefully spurred by this thesis. Widespread adoption is a decade or more away. While such revolutions tend to take several decades, there appears to be enough interest, a great enough need, and it seems to fit the practical models that it may arrive sooner. It is starting to be practiced at Syncrude Canada Ltd's oil sands mines, and elements of each are present at other mines.

5.8 Supporting successful reclamation

Successful reclamation, as defined in Chapter 4, is the goal of landscape engineering. While most of the efforts in landscape engineering revolve around only a few of the elements of successful engineering, mainly closure planning, goal setting, and landscape design, the remaining elements are also required for the landscape engineering to be successful.

The landscape engineering team will need to ensure these elements are in place. They will need to ensure there is active management support. They will likely lead the stakeholder involvement and communication efforts. The team will be the creator and link between closure planning and getting it implemented through the organization. They will be identifying, directing and perhaps performing research and development. They will be implementing as major tools useful economics and decision making, risk management, and creating the environment with an independent audit. They will build upon and continue to advance the operational and technical know-how. Through good management, they will make these work together to achieve successful reclamation. The office costs (staff and consultants) for this effort is considerably higher than present, but not that dissimilar to the effort of present geotechnical costs.

5.9 Conclusions

Landscape engineering is introduced as a specialized branch of civil engineering aimed primarily at mine reclamation at the landscape scale. It is a composite of the many physical science, biological science, and engineering disciplines involved in mine reclamation. Landscape engineering addresses the creation of reclaimed landscapes that meet the goals of mining companies (and their regulators) during mine operation and those of society and the next custodian after mine closure.

It is a logical step in the evolution from a largely piece-meal artisan approach to reclamation, that despite its successes, is generally unable to produce landscapes that are certifiable and can be transferred to willing custodians. A more thorough and thoughtful integrated approach is indicated, building on the strengths of past work and methods.

Narrowly defined, landscape engineering is the application of mathematics and science to create useful landscapes. But both more broadly and specifically, landscape engineering is the interdisciplinary application of engineering and other applied sciences to the design and creation of anthropogenic landscapes, usually guiding mine reclamation, but also for other large civil earthwork projects.

Though landscape engineering embodies all elements of traditional engineering (planning, investigation, design, construction, operation, assessment, research, management, and training), it focuses on three main areas: planning (especially closure planning), landscape design, and landscape performance assessment. The ongoing iterative process of planning, design, and performance assessment is the basis of landscape engineering work.

Closure planning includes goal setting and design of the landscape as a whole. Landscape design is more focussed on the design of individual landforms to reliably meet the goals as set out in the closure planning process. Performance assessment acts as feedback to the planning, design, and construction processes, and also help to indicate liability, risk, and levels of financial assurance.

Core specialists of the landscape engineering team include mine planning, geotechnical, hydrological, groundwater, soils, vegetation, and wildlife experts. Others will be incorporated as needed or available. Larger mines will have a dedicated staff, most mines will employ consultants on an as needed basis.

Technologies unifying landscape engineering that make landscape engineering a discipline rather than a collection of scientists, engineers, and other reclamation specialists include reliance of flux models and risk management techniques for landscape design, construction, and operations. The team working together will focus on supporting the mines need for successful reclamation.

Landscape engineering has the added benefit of being inevitable, but not perhaps under the same name. It is likely to follow the typical path of other disciplines, driven by need and technology to becoming an inclusive and useful method of economical creation of landscapes in the service of humankind. Full adoption, however, is likely to spread slowly over the next several decades.

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Table 5-1 Performance of various disciplines

Specialty	Aspects with fair to good performance	Aspects needing improvement
Mine planning	• Bulk material handling • Scheduling	• Adoption and new landscape engineering constraints and re-optimization of mine plans and techniques
Geotechnical	• Short and medium term slope stability • Trafficability and roads • Cover design	• Long term stability predictions • Subsidence predictions • Soft tailings bearing capacity and performance
Groundwater	• Seepage calculations • Offsite groundwater contamination modelling	• Integration of on-site and off-site groundwater considerations • Integration with soil water • Prediction of long term groundwater and effect on geotechnical stability
Surface water hydrology	• Tools well developed	• Application of tools
Soils	• Coversoil placement techniques • Empirical methods for determining optimal soil thicknesses	• Soil moisture and contaminant considerations
Vegetation	• Use of agronomic grasses and legumes for ground cover • Reforestation	• Ecosystem based approach • Long term succession prediction • Tailored planting • Native species
Wildlife	• Short term planting strategies • Short term enhancements	• Landscape scale ecosystem development • Long term rationalization
Traditional environmental knowledge		• A new area to be explored.

Table 5-2 Landscape engineering compared to some related disciplines / systems

Type	Professions involved	Disturbance Scale, ha	Goals	Typical applications	References
Landscape engineering	Geotechnical, mining, groundwater, hydrologist, soil scientist, vegetation, wildlife, others	Landform, landscape and region 10^2 to 10^5	Meeting agreed upon goals, especially long term landscape performance	Mining	This chapter
Traditional reclamation	Biologists, mining engineers, soil scientists	Landform 10^0 to 10^4	Greening up the landscape, making it safe	Mining, other disturbances	Carrel, 1980; Lyle, 1987; United States Bureau of Mines, 1988
Landscape architecture	Landscape architects	Building lot, civic park 10^{-3} to 10^2	Usually aesthetics	Gardens	Tobey, 1973; Marshall and Hiss, 1981; Simonds, 1998
Landscaping	Landscapers	Garden, building lot 10^{-3} to 10^0	Groundcover, aesthetics	Home, businesses, civic facilities	American Horticultural Society, 1982; Ingels, 1997
IS 14001 environmental management system	Accountants	Not specified	Meeting agreed upon goals	Mining, industrial	ISO, 1998; Schoffman and Tordini, 2000; Hillary, 2000
Ecological engineering	Ecologists	Landform 10^0 to 10^2	Making the land productive and useful	Wetlands, other civil works	Mitsch and Jørgensen, 1989; Jørgensen, 1989; Yan et al., 1993
Coastal engineering	Civil engineers, geomorphologists, vegetation experts, land use	Landform, landscape 10^1 to 10^3	Changing or repairing shorelines for human use	Beaches, harbours, breakwaters, storm protection.	Kaufman and Pilkey, 1983; United States Army Corps of Engineers, 1984; Cameron, 1998
Bioengineering / biotechnical engineering	Soil scientists, vegetation specialists, civil engineers, foresters	Slopes 10^{-2} to 10^2	Slope erosion stabilization	Slope cuts, gully repair	Schiechtl, 1980; Gray and Sotir, 1996
Planetary engineering / geoengineering / terraforming	Atmospheric scientists, planetary scientists	Whole planet 10^{10}	Changing atmosphere to make more habitable for humans	Proposed changes to earth's atmosphere, terraforming other nearby planets	Sagan, 1994; Huyghe, 2000

Table 5-3 Landscape engineering compared to civil engineering

Aspect	Traditional civil engineering	Landscape engineering
Design life	Finite, often decades	Good performance is expected forever
Maintenance	Specified maintenance and monitoring expected or repairs as needed	Landscapes are usually designed to be maintenance free
System complexity	Usually simple	The systems are complex dynamics threshold with many interacting forces – external and internal, many or most of which are unknown
Scale	Usually <1ha to tens of hectares. Sometimes long linear disturbances like roads and pipelines	Landscape scale, thousands of hectares
Participants	Civil engineers, sometimes other engineers	Multidisciplinary teams.
Costs	Typically millions, profit centred	High cost — many times the land value and usually tens of millions up to billions (but usually a small fraction of the annual mining budget).
Materials	Well chosen easy to work with materials	Dealing with large volumes of mine waste often environmental sensitive
Failure implications	Range from low to high	Range from low to high
Construction timeframes	Usually several years	Usually decades
Regulatory framework	Well defined, often codified	Poorly defined, sometimes open ended
Stakeholder involvement	Usually limited, one time	Extensive, ongoing
Forces and pressures	Usually some control	Have to take what's coming
Present success rate	High	Low where poorly practiced

Table 5-4 Emergence and development of various engineering disciplines

Age	**Groundwater**	**Geotechnical**	**Coastal engineering**	**Irrigation (subsurface drainage) engineering**	**Aeronautical engineering (powered flight)**	**Surface-water hydrology**	**Landscape engineering**
Artisan period	Observational, antiquity through mid 1800s	Antiquity until 1900s	Trial and error through 1950s	Rule of thumb since 5th century BC	Glider flights starting 1890	Irrigation and aqueducts 3200BC to mid 1600s	Reclamation 1970s
Quantitative, empirical basis	Henry Darcy (1856)	Karl Terzaghi, *Erdbaumechanik* (1925)	Wave forecasting 1940s, 50s Beach dynamics 1970s	Nomographs, 1960s	Wright Brothers 1903	Perrault, Mariotte, Halley 1600s	1990s
Application of mathematics, framework	Dupuit (1863)	Karl Terzaghi *Theoretical Soil Mechanics* (1943)	Wave mechanics- Airy 1845, Stokes 1880 Stream function wave theory 1970 Beach mechanics 1970s	Completion of design equations 1920s	Military planes 1940s	Hydrologic cycle and continuity equations 1700s	Design for closure 1972 Closure planning 1985 Landscape design 1995 Reclamation water balance 1995
Widespread use	Fluid potential Hubbert (1940)	Terzaghi (1943)	US Army Corps of Engineers (1954)	Government irrigation projects 1940s	Military planes 1940s	1800s	2010?
Subsequent advances	Early numerical models 1970s Widespread numerical modelling 1990s	Early numerical models 1970s Widespread numerical modelling 1990s	Recognition of limitations 1990s	Finalization of various methods 1960s Computer applications 1980s	Supersonic military planes 1953	Numerical modelling 1970s Widespread numerical modelling 1990s	To come
Historical reference	Freeze and Cherry (1979)	Goodman (1999)	United States Army Corps of Engineers (1984)	ASCE (1998)	Vincenti (1990)	Biswas (1970)	This thesis

Chapter 6

Geostatistical analysis of oil sands tailings sand hydraulic conductivity

6.1 Introduction

Landscape engineering recognizes that some elements of landscape performance are controlled by the variability of certain parameters rather than by their average or design values. The geostatistics of spatial variability is already being applied in many related fields including landscape ecology, soil science, geotechnical engineering, and prediction of performance of water and oil reservoirs, but more often at the research level. It provides frameworks and analysis tools for the landscape engineer to apply to a variety of challenges.

One of the central analytical tools in landscape engineering is the water balance. To predict fluxes of groundwater, deep percolation (recharge) and substrate hydraulic conductivity are key parameters and also among the ones with the most variability and uncertainty. This chapter provides an example of a simple empirical geostatistical framework for tailings sand hydraulic conductivity (a fairly homogeneous artificial substrate). It demonstrates scale effects on means, variances, and coefficients of variation, and it discusses the use of autocorrelation and the semivariogram to describe spatial variability as well as upscaling techniques. In particular, it applies the frameworks of Phoon and Kulhawy (1999a) on geotechnical coefficient of variation, Schulze-Makuch et al. (1999) on scale effects, DeGroot (1996) on spatial variability, and Desbarats (1992) on power law upscaling to tailings sand permeability as a method in order to introduce these tools to landscape engineering.

6.2 Background

Prediction of groundwater seepage is an essential element of geotechnical and geoenvironmental engineering and hydrogeology and a critical element of landscape engineering because it affects the physical, biological, and chemical performance of landforms and landscapes. Failure to correctly assess groundwater seepage in landscape design may lead to widespread areas failing to achieve acceptable landscape performance.

Understanding hydraulic conductivities of landscape substrates is key to reliable prediction because they have a large impact on fluxes, pore-water pressures, and water table locations. The extremely large range of saturated hydraulic conductivities for various rock and soil types is well known but the spatial variability and scale effects of a given material are underappreciated and seldom considered explicitly in routine groundwater hydrology practice, undergraduate textbooks, or mine reclamation practice. The geostatistics of hydraulic conductivity, however, is an area of ongoing, intense, sophisticated academic investigation and there is a vast literature, most of which is rather daunting for non-mathematicians. There is little accessible guidance for landscape engineers and other practitioners.

For tailings structures (dykes, dams and ponds) and many groundwater resources projects, the state of practice implicitly compensates for this limited understanding. For example, practitioners predicting seepage discharge rates, tend to select among the highest hydraulic conductivity values from laboratory testing for most designs. Greater confidence is placed in larger scale tests and where practical, testing and back analysis is done at the same scale as the design. The underlying rationale is that there will be well-connected higher hydraulic conductivity zones (preferential flow zones) that will govern field performance that are often undetected in laboratory tests or small scale field tests. A combination of using upper-bound hydraulic conductivity and generous conservatism in seepage design, especially in use of generous supply-to-demand ratios for internal drainage systems, has allowed reasonably good operational performance. For cases where fluxes and water table elevations need to be controlled to certain maximum operational values, these design practices have an accepted record of success and involve a modest effort in engineering and testing. To reduce residual uncertainty, monitoring is employed and remedial measures realized if acceptable performance is not achieved. The state of practice does not include the explicit use of geostatistics but it is generally handled implicitly.

But when it comes to prediction of the behaviour of seepage plumes, and especially the performance of liners, covers and other aquitards meant to have low seepage rates, many predictions grossly underestimate seepage fluxes and contaminant transport velocities, mainly from small undetected high hydraulic conductivity zones or a poor understanding of groundwater flow mechanisms (e.g., Sarewitz et al 2000). It seems that some of the problems come from a failure to appreciate geostatistics – especially the variability, upscaling, and short autocorrelation distances of hydraulic conductivity (Benson, 1991). Of particular interest to the landscape engineer is the effect of spatial variability on deep percolation through unsaturated covers – small areas of undetected higher vertical permeability (often due to macropermeability) may govern performance of the cover (and the landform) as a whole.

Landscape engineering is not only interested in predicting maximum rates of seepage and controlling water tables through civil engineering means. It is also interested in the variability in water table location (as an element of performance, diversity, and risk), the ranges and temporal changes in seepage fluxes (as influent to, or effluent from, wetlands and other aquatic landscape elements), rates of ionic movements and dilution or concentration, prediction of deep percolation through covers, flushing mechanisms within vegetation root zones, and soil moisture availability to plants, usually in the absence of ongoing human intervention. In other words, it is both interested in the geographic (spatial) variation of performance on a landform (especially near surface) as well as the temporal fluxes of large and small watersheds to the rest of the landscape. This interest comes from the necessity of trying to achieve or balance often competing objectives and because it is often impractical (or impossible) to use a purely conservative or even deterministic approach. A probabilistic approach with ranges of possible outcomes will become a common feature of landscape engineering as a part of risk-based approaches to evaluate various design options. Of all aspects of landscape performance relating to seepage, the most important issue is often the seepage water quantity and quality where it interacts with the biosphere.

For traditional tailings dyke design, when the design permeability is incorrectly selected, the design is changed during construction. Based on analysis of performance during early construction, drainage schemes may be altered (additional drains may be installed (or omitted), seepage cutoff walls may be installed, rates of dyke rise may be increased or decreased – it is common for a tailings dyke to go through several design phases during its life. Most of the design change cost the mining company money, either in the form of additional construction costs, or lost savings in starting a non-optimal design. In the worst case, poor design and management can lead to dam failure. Managing these risks is a standard and accepted part of dyke design and construction. Risks are often managed early on by using conservative values for permeability and fluxes.

When the wrong permeability (or percolation) values are selected (or ignored) relative to long term landscape performance, common results are uncontrolled seepage plumes, water tables that are too high or too low (or waters to salty or contaminated) to support intended soils and vegetation (and land use), increased erosion, and reduced trafficability. Fluxes of seepage water reporting to water treatment facilities may be much higher than anticipated. Downstream land uses that require certain quantity and quality of water are often affected. In general, selection of the wrong design permeabilities result in high reclamation costs and extensive post-closure retrofits or acceptance of reduced landscape performance and land use limitations often result. Because of the inherent uncertainty in any prediction of long term landscape performance, accommodation for this uncertainty, including some degree of retrofitting, is likely required in any case.

The key factors in landform water balance are estimates of the annual deep percolation rate (groundwater recharge rate), average groundwater gradients, and the substrate hydraulic conductivity. The greatest uncertainty often lies with the substrate hydraulic conductivity and is the subject of this chapter.

Study location

The Syncrude Canada Ltd Mildred Lake Operation in northeastern Alberta, Canada, is one of the largest mines in the world (Figure 6-1). It processes approximately 450 000 tonnes of oil sands each day and generates about 250 000 cubic metres of tailings sand. The tailings sand is slurried in pipelines to several deposition sites where it is used to construct large tailings dykes and settling basins through hydraulic deposition. Syncrude's Mildred Lake Settling Basin, MLSB, (Nicol, 1994) and the Southwest Sand Storage Facility (List et al., 1997) are two of the largest volume earth structures in the world. Upon closure, tailings sand will form 100 square kilometres of the reclaimed landscape (Syncrude Canada Ltd, 2001). Other oil sands mines also produce similar tailings sand that will also occupy the majority of their closure landscapes. Understanding short-term and long term groundwater and seepage performance of landforms constructed or capped with tailings sand is critical to good landscape performance in the region.

Tailings sand material properties and behaviour

Syncrude oil sands tailings sand is loose to dense, uniform, light grey to brown, moist to wet fine sand, composed almost entirely of quartz. It is subangular to subrounded, weakly subhorizontally bedded with trace amounts of bitumen and clay with infrequent thin, medium grey, horizontal, clayey silt layers with a porosity averaging about 40 percent. It is often considered to be geotechnically homogeneous, but anisotropic with respect to permeability. Fluvial and deltaic lithofacies are recognized within the deposits.

During extraction of bitumen from the oil sands, the fines fraction is highly dispersed. Unlike most metal mines tailings beaches, the grain size of oil sands tailings sand (Figure 6-2) shows no measurable trends down the beach. The fines are so dispersed within the carrying fluid, that the segregation of the fines and the sand is uniform – the runoff water with fines is carried to the pond, the remaining fines are trapped with the pore-water. In that the density (and hence the porosity) has a narrow range, so does the fines content. Movement of fines or bitumen may impact the overall bulk permeability of the tailings sand. Strong interlayering of fines and sands is observed at the pond / beach interface. Much of the fines in the pore-spaces of the sand matrix are mobile and seeps from test pits and into wells are usually cloudy.

There are several placement methods for oil sands tailings sand that range from compacted cell construction (for dyke construction), overboard beaching, to mechanically regraded downstream slopes (Handford et al., 1982; Nicol, 1994; List and Lord, 1996; List and Lord, 1997). These different deposition methods may impact permeability. There is also the assertion that the permeability decreases with depth or age (Alberta Department of the Environment, 1977) likely due to densification by increased confining stresses. Pore-water chemistry may also have an impact on permeability because of its effects on clay dispersion and entrapment. Laboratory testing indicates that the effects of density and fines content can have significant impacts on permeability (Figure 6-3) but shows considerable scatter. The present study does not generally differentiate between these material placement types, density, confining stresses, age, pore-water chemistry, or fines content because this information is unavailable for most field tests and many laboratory tests. The exception is near-surface tailings sand which seems to have its own permeability distribution (Section 6.3.15). Disregarding these other variations likely increases the observed variance (and coefficient of variation) in the measured permeability values, especially at smaller scales, and contributes to the "nugget" variance for semivariograms discussed in Section 6.7.

6.3 Permeability data by test method and scale

This section summarizes the methods used to generate the database of tailings sand permeability. Most of the methods are common to tailings engineering. While some data was available in reports from the past thirty years, most of the data in the present database was generated through field and laboratory work in 2000 and 2001. Subsections are arranged in order of increasing test volume from small lab tests to dyke section back analyses and span eleven orders of magnitude in volume tested and seven orders of magnitude in permeability. Test methods are described below and permeability is summarized in Table 6-1 and Figures 6-4 through 6-6. A printout of the permeability database is presented in Appendix C. Details of test methods and analysis methods are presented in Appendix D.

Where tailings sand samples are required for laboratory testing, they are usually gathered from shallow pits dug in a tailings sand beach or cored from frozen beaches in midwinter at convenient locations. Field tests occur on dyke slopes, crests, and beaches. Grid sampling occurs sometimes, randomized sampling has never occurred.

Test pits in tailings sand beaches show some subhorizontal bedding of slightly finer and slightly coarser layers, which would suggest a higher horizontal than vertical permeability. Permeability testing discussed below further suggests that there is a seemingly isotropic conductivity (k_s) from beach surface tests and intact surface samples. Based on these observations, the test data are divided into three populations: horizontal conductivity (k_h), vertical conductivity (k_v), and isotropic near surface conductivity (k_s).

Most test volume calculations are only approximate, but the small errors do not greatly affect the results since the volumes of all tests vary over many orders of magnitude. Following methods from Schulze-Makuch et al. (1999), the bulk volume of the sand is used. (An alternative measure is to estimate an average flow length – for example the height of a laboratory sample, the reach of a well, or the length of a cross-section). For field injection or withdrawal (slug, percolation, infiltration) tests the volume is estimated by the total volume of water added or drained divided by the porosity. For back analysis of dyke cross-sections, the test volume is estimated by using a flow width of ten percent of the length (based on typical dispersion relationships) and an average vertical flow thickness. These volume calculations ignore the biases of converging flow such as in radial flow to wells (or from standpipes) or vertical thinning of cross-sections from crest to toe.

Because the tailings sand is fairly homogeneous, much of the large-scale permeability data falls within two orders of magnitude and some of the findings and analyses are subtle. In most cases, there is enough data to provide statistically representative means and variances.

6.3.1 Laboratory intact sample constant head tests

Twenty-three permeability tests were run on small intact cores from naturally frozen tailings sand. Fifteen-centimetre diameter cores of frozen shallow beach sand from the frost zone were collected. In a cold-room, the samples were subcored to nominal 2-cm diameter and 7-cm height – one vertical and one horizontal subcore were taken from each field core to investigate anisotropy. These subcores were placed into a triaxial cell, backpressure was applied, the sample then thawed and tested under nearly saturated constant head conditions.

Data are presented in Figures 6-5C and 6-6. Samples showed about two orders of magnitude variation and are likely indicative of surface permeabilities (k_s). There is no correlation between horizontal and vertical permeabilities from the same core ($r^2 = 0.005$) and using the t-test for paired data, there is no statistical difference in the mean horizontal and the mean vertical permeability ($\alpha = 0.05$). Based on this testing, it is assumed that for surface sands, there is no consistent anisotropy permeability ratio and that *on average* the ratio is close to unity. Further testing is needed to strengthen this conclusion. The database assumes each test result is a unique isotropic surface permeability measurement (k_s).

6.3.2 Laboratory reconstituted permeameter tests

This method involves compaction of homogenized sand into a Proctor mould to a prescribed density and moisture content. Porous stones (or layers of fine gravel with wire screens) are placed on the top and bottom of the sample and water is passed from the bottom to the top of the sample. The sample is likely only 80 to 90% saturated by this process – it can be said to reach "field saturation" (Hillel, 1982) under upward flow. For oil sand tailings sand, care needs to be taken to avoid blinding filter paper and porous stones with dispersed fines that migrate from the sample. Typically, a half dozen falling head tests or a constant head tests is performed until permeability measurements reach steady state. It is usually assumed that these reconstituted test volumes are generally representative of horizontal permeability (k_h). While this test method has limitations (e.g., it is not fully saturated, it is a small-volume remoulded sample, it typically uses high gradients, and compaction likely introduces some heterogeneity), it is the mainstay of characterization for tailings geotechnique because it is simple, fast, and does not require intact samples.

Data are presented in Figures 6-5B and 6-6. The results show a relatively low mean and a range of two orders of magnitude. The restricted range is perhaps because the samples were all collected from a small area (20-litre auger samples collected along a 50-m long strip down a tailings sand beach).

6.3.3 Undifferentiated laboratory tests

Many of the laboratory permeability values recorded in internal Syncrude reports do describe the sample collection, preparation, or test methods. Most involve reconstituted samples prepared in Proctor moulds and using constant or falling head, with a few samples under triaxial stress conditions.

Data are presented in Figures 6-5D and 6-6. These tests showed five orders of magnitude of variation. Permeabilities are sensitive to compacted density and fines contents (Figure 6-3). Some permeability values from these tests are very low, which either may be indicative of a second population (statistical outliers that do not fit the lognormal probability curve), represent errors in sampling or testing (perhaps reflecting unsaturated permeabilities), or they may be true extreme values. In some analyses presented here, these data have been combined with the more recent laboratory tests (Section 6.3.3) and referred to as "All laboratory data."

6.3.4 Field percolation test

A series of rapid "coffee-can" percolation tests were done on two unsaturated tailings sand beaches to demonstrate autocorrelation distances (see Section 6.7.2). These tests involved pushing 17-cm high, 15-cm diameter cans (with both ends removed) to a depth of 5 cm at 1.0-m intervals down the beach – a long series of simple single-ring infiltrometer tests. Each can was quickly filled (10 seconds) with tailings water and the water level from the top of the can was measured at three, six, and nine minutes. Flow neared steady state in the second three-minute interval. A series of 100 percolation tests were run at two tailings sand beaches (MLSB Cell 16 and 25). The percolation rate (mm/min) was converted to a surface permeability using a Hvorslev (1951) slug test formulation (see Appendix D for details) which was checked against a Seep /W transient groundwater analysis.

Data are presented in Figures 6-5E and 6-6. The permeability results are higher than might be expected, likely for two reasons. First, single ring tests will be inaccurate, if there is leakage inside or outside the ring, as is likely the case with these particular tests. Finite element seepage back analysis reveals that leakage effects are secondary to natural variations in permeability. It seems more likely that the recorded values may be indicative of permeability at the ground surface but they systematically slightly overestimate the permeability as compared to more reliable surface test permeability methods.

6.3.5 Field surface infiltration tests

Field surface infiltration tests were run by others using Guelph and double-ring infiltrometers. Results were based on steady state infiltration of water into the tailings sand surfaces (with some tests run a few centimetres below surface).

Data are presented in Figures 6-5E and 6-5F and 6-6. Data have about two orders of magnitude of variability. The high permeability values are classified as surface permeability (see Section 6.3.16).

6.3.6 Field falling head standpipe slug tests

The falling head test (also known as an overdamped slug test) using a standpipe piezometer is a common method to determine field permeability. Standpipes are installed with a discrete open zone of known length and diameter at depth. The initial static water level is measured then quickly raised or lowered and the changing head measured as the standpipe re-equilibrates. Data are fitted to a curve and the permeability calculated from measured data. Most tests for this chapter involved adding eight litres of water to the standpipe and recording the falling head over time using a datalogger. Numerous methods of analysis are available; the data here were analyzed using a method developed by Hvorslev (1951). The resulting data are assumed to be indicative of horizontal permeability. A k_h/k_v ratio of 1.0 was assumed in the analyses – in reality, the ratio likely varies at each location.

Data are presented in Figures 6-4, 6-5G and 6-6. Results varied over two orders of magnitude and are thought to be reasonably accurate. Repeat tests on later dates usually yield results within 5 to 20% of original values suggesting a measurement error (ME) coefficient of variation (of log transformed data) of about 3 to 5 percentage points. There are no observable trends relating test location or depth for these 192 tests. The standpipe permeabilities form the best dataset in this chapter because they evaluate a wide variety of sand materials using a standard test method.

6.3.7 Laboratory model tests

Two types of two-dimensional laboratory model tests were performed to demonstrate flow mechanisms for two geometries. The first used a 6-m long, 0.3-m wide plywood flume with outlets that simulate subsurface drains. Tailings sand was slurried to form a constant thickness of 0.3 m The second model was a flushing experiment using a 1:100 scale model dam cross-section of Syncrude's SWSS at a overall 20H:1V downstream slope angle. The model was 7-m long, 0.3-m wide, and 0.3-m high and made from plywood and Plexiglas. Moist homogenized tailings sand was compacted by hand and was assumed to be saturated after being water-capped for several weeks. Experimental results (steady state and transient) were back analyzed using analytical and finite element methods with good agreement between these analyses.

Data are presented in Figures 6-5H and 6-6. Back-analyzed hydraulic conductivities ranged over one order of magnitude and were relatively high, possibly due again to the shallow, isotropic nature of the test deposits.

6.3.8 Field tailings sand cell construction dissipation tests

This method involves measuring pore-water pressure dissipation of a lift of tailings sand that was quickly loaded with a second lift. Each lift was about 5-m thick and the representative test volume is estimated at about 100 m^3. Consolidation occurred in about three days. The situation was modelled using one-way vertical upward drainage.

Data are presented in Figures 6-5I and 6-6. Vertical permeabilities of 10^{-6} to 10^{-4} cm/s. were found.

6.3.9 Field pump test

There is a paucity of well-pumping data for oil sands tailings sand, mostly because mechanical dewatering has not been needed to date and partly because the fine sand tends to flow into the well, quickly clogging the intake and pump. In 2000, a very short (2-m long, 0.4-m diameter) pumping well and 16 observation wells arranged in four perpendicular radiating lines, were installed in a 6-m thick beached sand cap overlying less permeable soft tailings. The well was installed using a small backhoe because the site was untrafficable to drill rigs. The well screen was surrounded with geotextile to prevent the sand from flowing into the well. Two pump tests were run, producing a steady state discharge of 0.5 L/min (a very low discharge) over six days. Drawdowns were about one metre near the pumping well and the reach was about 20 m. Permeability was calculated for each pair of wells on each of the four lines.

Data are presented in Figures 6-5J and 6-6. The half order of magnitude range of measured permeability values produced by this test indicates a combination of model and measurement error and perhaps the spatial variability over the area of the test. It may provide insight into the effects of convergent flow.

6.3.10 Field gradients between standpipes

At Syncrude's MLSB, there are 33 instrumented tailings sand dyke cross-sections with pneumatic and standpipe piezometers installed. Sections are typically 400 to 2000 m long and 30 to 50 m high. Additionally, there are filter drains at various levels within the structure that provide two crucial pieces of information – they are sites of zero excess pressure (a known head at a known location) and they provide a measure of the seepage flux through the section (albeit over a broad cross-sectional area). The analysis ignores deep percolation of rainfall, evapotranspiration, and any underdrainage (because different cross-sections are influenced by these factors to different extents, this will increased the observed variability of the results). Measured average fluxes and gradients between pairs of standpipes and between standpipes and drains allow an estimate of the average permeability between these locations. The horizontal permeability is calculated using simple Dupuit-Forchheimer seepage theory (Kirkham, 1967).

Data are presented in Figures 6-5K and 6-6. Three orders of magnitude of scatter, with half the data within half an order of magnitude were found. The large range is mostly due to the simple analytical model and simplified geology (model error) and smaller measurement errors of head and flux. Formal back analysis using finite element analysis (Section 6.3.13) overcomes much of this model uncertainty.

6.3.11 Dyke section seepage back analysis (1998)

Thirty-three instrumented cross-sections from MLSB and four from the SWSS were back analyzed using a finite-element groundwater / seepage model (Seep/W). Typical sections are 700 to 2000 m long and 25 to 40 m high (Figure 6-7). The model geometries extended from 300 m into the pond to beyond the toe of the structure and included an impermeable base (located either directly below the tailings sand where it lies immediately on top of glacial till or glaciolacustrine clay or below a glaciofluvial aquifer.) (In reality, the lower boundary will not be completely impermeable, but is likely at least several orders of magnitude lower permeability than the tailings sand). It was assumed that 20 percent of annual precipitation percolates into the structure (groundwater recharge) and that the seepage was essentially at steady state. For the SWSS, recharge rates of 40 percent of annual precipitation were assumed for the unsaturated portions of unreclaimed beaches. These recharge rates are based on one-dimensional modelling, field observations, and back analysis, but contain considerable uncertainty. The contribution of precipitation to total seepage flux depends on the length of the beach and slope and ranges from 5 to 100 percent with most sections estimated between 20 and 40 percent. The sections were back analyzed to match piezometric data and total seepage flux at year-end 1998, with an emphasis on matching the flux as closely as possible by adjusting vertical and horizontal permeabilities.

A detailed description of the method is presented in Appendix D. Data are presented in Figures 6-5K and 6-6. The resulting permeabilities have a range of about one order of magnitude.

6.3.12 Dyke section back analysis (historical)

This section is similar to Section 6.3.11, but provides final back analyzed values from consultants' reports. Some of the analyses were done graphically by hand with flow nets; others were done with early in-house mainframe finite-element seepage models.

Data are presented in Figures 6-5M and 6-6. Back-analyzed values were similar to those reported in Section 6.3.13.

6.3.13 Historical design values

Not included in the figures are the assumed values for design of oil sand tailings dykes. While not a true measure of permeability, the database includes values used for design by professional engineers and geologists based on staff and consultants' reports. Most are used for seepage design for dyke cross-sections.

The choice of dyke design permeability values is largely a matter of style. Prior to 1987, a horizontal permeability, $k_h = 2 \times 10^{-4}$ cm/s was the most common dyke design value and after 1990, $k_h = 8 \times 10^{-4}$ cm/s was preferred. Prior to 1987, k_h/k_v ratios from 1 through 16 were employed, whereas after 1990, a value of 16 predominates. Prior to the present work, Syncrude had adopted a single design value for k_h of 8×10^{-4} cm/s with a $k_h/k_{v\ ratio}$ of 16 for all oil sands tailings sand for all scales, depths, and designs. The permeability ratio is based on analysis done using transformed flownets near internal drainage filters on a nearby tailings dam (McRoberts, 1996). Sensitivity analysis by varying k_h and k_h/k_v is common, and some consultants still employ different design values.

6.3.14 Horizontal to vertical permeability ratios

It was originally hoped that results from this study would confirm the typical horizontal to vertical permeability ratio for dyke design of 16 for oil sands tailings sand.

The lack of statistical difference between horizontal and vertical permeabilities from the frozen core samples (Section 6.3.2) suggests that the k_h/k_v ratio varies from sample to sample for small surface tests and may average about one. Back analyses of dyke sections is somewhat insensitive to k_h/k_v ratio (because they are dominated by horizontal flow), and values of 1 to 20 are common. For other test methods, the effects of vertical permeability are overwhelmed by other factors (model and field errors) and provide little insight into this ratio.

The k_h/k_v ratio is not a unique number – it varies with scale, spatially, and likely has its own statistical distribution. In the absence of compelling data, the following ratios are recommended for design. For sands within 2 m of the beach surface, an average ratio of one is recommended with values between 0.1 and 10 considered in sensitivity analysis. For designs involving larger volumes, such as for pumping or other drainage schemes and for dyke design, an average ratio of 10 is recommended (rather than the precision implied by the number 16) with average ratios from 1 to 20 considered in sensitivity analyses.

6.3.15 Surface sample permeabilities

Data from the very shallow tests should be considered separately from the rest of the database. Recognized some twenty-five years ago (Alberta Department of the Environment, 1977), this conclusion seems to have been lost until the present study. In particular, the lab field frozen cores, field percolation, field Guelph permeameter, and field infiltration tend to produce higher permeability values than other methods. The reason for the permeability difference is not clear – surface materials generally have similar densities (measured by field nuclear densometers) as deep sands and have the same lithology and stratigraphy. The difference may lie with confining stress, near-surface macro-permeability, or subtle density effects. The percolation tests likely also suffer from significant experimental and model error – most of the comparisons of means and variances between the four surface test datasets indicates they are significantly different from each other ($\alpha = 0.05$).

Recognition of this surface layer as a distinct material (with respect to permeability) is important to modelling and design of covers and percolation. Methods of determining permeability of these shallow deposits are sensitive to the sample location and testing method. Near-surface tailings sand permeability is relatively high, and similar to that of coversoil layers commonly employed in reclamation, potentially creating areas of perched water tables within the reclamation material and limiting percolation into the underlying tailings sand substrate. The depth of this surface layer of high permeability has not been determined, but is likely less than about 2 to 3 m based on the observation that shallow standpipes (with the top of the screen at 2 m depth) do not seem to reflect this high permeability.

6.4 Means, variances, and coefficients of variation

6.4.1 Descriptive statistics

Excluding the shallow tests described above (Figure 6-8), it is interesting to note that there appears to be an upper bound of permeability of 10^{-3} cm/s at all scales. The lower bound varies over five orders of magnitude at small scale and one order of magnitude at larger scales. It is concluded that at larger scales, there is preferential flow through the zones with the higher permeability, though even at this larger scale, there is still some variability. The mean value of permeability increases with increasing scale volume to a constant value. Section 6.5 deals with these scale effects.

The distribution of permeability values from each test method generally have a strongly positive skewness – they are skewed towards the lower values of permeability (see Figures 6-4 and 6.5). The distribution of the data can be approximated with several common statistical distributions, and like most geological data, with a lognormal distribution.

Figure 6-4C plots the log transformed distributions from the standpipe slug tests and the dyke seepage back analysis against standard normals – a probability plot. That the log-transform data from each method falls on a straight line confirms the goodness of fit to lognormal distributions and helps to indicate potential statistical outliers.

Coefficient of variation, which is the standard deviation divided by the mean, is a useful measure of variation of geotechnical properties (e.g., Phoon and Kulhawy, 1999a; Phoon and Kulhawy, 1999b) for data (or transformed data) with a distribution that is approximately symmetric about the mean. The coefficient of variation for each dataset is listed in Table 6-1 and typically ranges from about 10 to 25 percent (for log transformed data with hydraulic conductivity units of cm/s) which is similar to that of other geotechnical properties of typical geotechnical materials as reported by Phoon and Kulhawy (1999a; 1999b). They are slightly greater than the coefficients of variation of 5 to 15 percent for log-transformed hydraulic conductivity of a wide variety of materials tests calculated from Schulze-Makuch et al. (1999) and 3 to 10 percent for unconsolidated materials by Bierkens (1996) and similar to those for fluvial sands by Rehfeldt et al. (1992). Thus coefficient of variation of log transformed permeability would appear to be independent of material type. Whether the effect of scale and test type on coefficient of variation is important will depend on the application.

Based on this study for large dykes, an average value for horizontal permeability (k_h) is interpreted 5 x 10^{-4} cm/s with a horizontal to vertical permeability ratio (k_h/k_v) of 1 to 20. Recognition of a range of values of about +/- a half order of magnitude (a range of 10^{-4} to 10^{-3} cm/s) is needed in design. Improvement on the accuracy of these numbers seems unlikely. It is worth noting that most previous analyses have ignored the influence of percolation of precipitation onto beaches and slopes and partial blinding of the reservoir by fine tailings. Both of these boundary conditions are important to the analysis of oil sands tailings dykes (and perhaps other dykes and dams as well), can be easily handled my modern groundwater and seepage modelling software, and should not be readily dismissed. As discussed below, sensitivity analyses can be supplemented or replaced with probability-based analyses using the data generated here.

While it is disappointing to only be able to predict design parameters and future performance within a range of one order of magnitude, this is a common outcome hydraulic conductivity, and more generally, for many environmental models. In many cases, coping with the uncertainty rather than trying to refine the parameters and models, is a preferable course (Sarewitz et al., 2000).

6.4.2 Sources of variability

Rock (1988) outlines independent sources of variability and errors in geological data especially related to sampling for ore grades. Adapted for hydraulic conductivity data in this chapter, the total error (TE) is a composite of geologic error (natural variability) (GE), instrument or sample preparation error (PE), measurement error (ME), and model or analytical error (AE) and can be estimated by:

$$TE^2 = GE^2 + PE^2 + ME^2 + AE^2 \qquad \text{Eq. 6-1}$$

Phoon and Kulhawy (1999a) present a similar equation based on equipment error, procedure error, and random error.

Variances and coefficients of variation reported in this chapter represent the total error (TE) – the natural variability (GE) will be somewhat less. Estimation of the individual components of error (or component of coefficient of variation) for each permeability test method is left to future study. Some generalizations, however, can be made.

Instrument and preparation errors (PE) involve subsampling and compaction irregularities for laboratory tests and disturbance (density and fines migration) for field tests. Measurement errors (ME) (which tend to involve measurement of water levels, instrument dimensions, and flows) tend to be small, especially compared to other errors. Model and analytical errors (AE) vary with each dataset and are affected by assumptions for boundary conditions, saturation, and often the choice of the modelling method (for example, there are numerous methods for analyzing slug tests and pump test data, each of which provides slightly different results for that same datasets).

It is difficult to estimate the non-geological error component of the total error. A sensitivity analysis of slug test data yields a ratio of about 3 between the highest and lowest values based on use of different common analytical models and simulating small measurement errors. The pump test data have a similar ratio of highest to lowest values permeability values of about 3 depending on which standpipes are used for analysis and this value would increase if different methods of analysis were also considered. Multiple laboratory reconstituted falling-head tests from a single bucket of tailings sand yields a highest to lowest permeability ratio of about 3. Analysis of various modes of drainage from the model flume yielded a range of about 7. Based on this cursory review, (PE+ME+AE) is estimated at typically just less than about a half order of magnitude for most of the datasets – this value corresponds to about five percentage points on the coefficient of variation. This is a small component of the coefficient of variation for small-volume tests, but likely most of the coefficient of variation associated with large-scale datasets (especially dyke seepage back analysis). Formal analysis and testing would permit refinement of this estimate. A method to reduce the effect of model error is to calibrate the model based on back analysis and use this calibrated model for future prediction. This is a common method in dyke design and recommended for landscape engineering.

One must also take care to avoid introducing additional error through statistical data manipulation, especially for data with skewed distributions. One should be especially wary of arithmetic averaging of data, which tends to emphasize higher values. Accurate classification of data is also critical to avoid creation of inhomogeneous datasets or bizarre or false outliers (Rock, 1988). Additionally accurate classification of outliers is critical to achieving good results from geostatistics as shown in the following sections – inclusion of false outliers or exclusion of true (geologic) outliers can have significant effects on some results, particularly for upscaling.

6.5 Scale variability

Figure 6-8A presents measured permeability as a function of test volume for non-surface tailings sand. The mean and variance are a function of the scale tested (Table 6-1). For small test volumes, the mean is low and the variance is high whereas the opposite is true for large test volumes. This reduction in variance with increasing test volume is common in geostatistics. The increase in the mean with increasing test volume is often observed for permeability data -- one can rationalize that the calculated average permeability of larger samples will be dominated by more permeable zones within the deposit, especially for horizontal conductivities of layered systems. Whether it is true for vertical permeability will depend more on the degree of interconnectedness of higher permeability zones. In some cases, overall anisotropy may be due to the spatial relation of layers rather than (or in addition to) anisotropy within elements (see Section 6.7).

For some methods, the variance is higher than might be expected based on the trends in Figure 6-6. This is likely due to sampling and model errors which result in a large nugget variance described in Section 6.7. This is particularly true of the gradient data (Section 6.3.11). This scale effect is well documented for the permeability (or transmissivity) of groundwater aquifers and petroleum reservoirs (Neuman, 1990; Neuman, 1994; Rovey and Cherkauer, 1995; Sanchez et al., 1996; Schulze-Makuch et al., 1999) but not yet commonly recognized in civil engineering.

Schulze-Makuch et al. (1999) provide a useful framework for describing scale effects. They plot log hydraulic conductivity (in units of metres per second) versus log test volume (in cubic metres) and fit the data with the following empirical equations:

$$k(v) = cv^{m};\ v \leq v_L \qquad \text{Eq. 6-2a}$$

$$k(v) = v_L;\ v > v_L \qquad \text{Eq. 6-2b}$$

where v is the test volume (in cubic metres), m is the scaling exponent that is the slope of the log-log plot, c is the empirical scaling coefficient (the permeability at $v = 1$ m^3), and v_L is the volume above which the permeability is scale invariant and the material above this volume may be considered quasi-homogenous.

From Figure 6-8A, the coefficients for non-surface tailings sand are estimated at $c = 1.3 \times 10^{-5}$ (m/s), $m = 0.4$, and $v_L = 10^{-1}$ m^3. This suggests that oil sand tailings sand straddles the line between natural homogeneous and heterogeneous porous flow aquifers. (Table 6-3). The mean reaches a constant value at about $v_L = 0.1$ m^3 which is a very small volume compared to natural deposits and characteristic of homogeneous deposits.

A similar analysis of the surface tests for tailings sand was also performed (Figure 6-8B). which yielded the same scaling exponent $m = 0.40$ with a scaling coefficient of 1.3×10^{-4} (one order of magnitude higher than the deep sands) and an upper-bound scale (v_L) of 10^{-3} m^3 (two orders of magnitude lower than that for deep sands). This analysis for the surface sand is less compelling than that for the deep sand, but seems to fit the framework. It is unfortunate that for neither of these datasets is there much data in the vicinity of v_L necessitating interpolation.

One would normally expect the variance of permeability to decrease with increased sample size, but this trend the database in Figure 6-8 is not clear. It is also notably absent from the data presented by Schulze-Makuch et al. (1999).

Some authors (e.g., Rovey, 1998) contend that much of the permeability scale dependency reported in the literature is due to use of different test methods at different scales. While a secondary effect for many heterogeneous materials (Schulze-Makuch et al., 1999), the effects of varying test methods could be more significant for homogeneous materials like tailings sand. Indeed, if laboratory testing were not performed, one would have concluded that the permeability of tailings sand is scale invariant. But regardless of the degree to which scale effects of oil sand tailings sand affect landscape performance, it is clear that the choice of permeability design values for landscape design based on small-scale tests must take into account testing or scale effects either implicitly or explicitly. The argument presented here is that for clarity and transparency in design and communication, explicit consideration of scale effects is preferable, and often a statistical distribution of values (rather than a single deterministic value) is warranted.

6.6 Upscaling

Upscaling is the process of estimating mean, (and often the variance and autocorrelation distance) at a larger scale than that of the available data. By way of definition, of interest is the *field* or *target scale*, data are available at the *support scale*, and numerical modelling is done at an intermediate *block scale*.

Neuman (1990) and Wen and Gomez-Hernandex (1996) present summaries of numerous sophisticated analytical and numerical techniques for upscaling hydraulic conductivity data. Methods include local techniques (those that consider only in-cell conductivities) that include simple and power averaging (discussed below), while others use renormalization, stream-tube, and flow anisotropy. There are also many non-local techniques (which consider boundary conditions as well). The above use rectangular blocks and grids, but many other gridding techniques can be employed. Some authors (e.g., Sanchez-Vila et al., 1996) question many of the basic statistical assumptions in the field of upscaling, particularly those of local techniques. While used extensively in the petroleum engineering, the science of upscaling is an area of intensive research and ongoing debate.

Most of these methods are beyond most landscape engineering and dam design applications. Instead, simple, local, empirical upscaling techniques are presented that may provide some guidance and insight to practitioners. The database may provide useful data for academic study relative to other geostatistical research on hydraulic conductivity.

6.6.1 Rule-of-thumb upscaling

Figure 6-8 provides an example of a very simple scaling technique if one is fortunate to have data at various scales. One simply uses the graph to interpolate a mean and variance at the target scale. One may choose to reduce the reported variance by estimating the non-geological error (see Section 6.4.2).

However, having such a database is rare. So a more useful approach is to test a large enough number of independent samples and select a certain percentile to determine a design value. One would attempt to test materials from a variety of locations and depths. Based on the present study on oil sand tailings sand, one would choose about 30 tests (a suitably large number) and, for the case of laboratory tests, select the 85th percentile as an initial design value for large scale applications (like predicting dyke seepage) because the 85th percentile of laboratory data corresponds to the average large-scale permeability. In the case of slug tests, one may estimate the average large-scale design value to also be equivalent to the 85th percentile. The variance at the large scale may be estimated as some fraction of the coefficient of variation. For the oil sand tailings sand, the coefficient of variation (of the log transformed data) of the slug test and that of the dyke sections is similar (10 to 15 percent). Where autocorrelation distances are high, it may be possible to conduct multiple independent tests at the same location to attempt to address the component of non-geologic coefficient of variation.

A third technique (explored in more detail below) uses simple averages. The arithmetic mean of any permeability dataset is often close to the upper-bound horizontal permeability and the harmonic mean is often close to the lower-bound vertical permeability. If the material is heterogeneous and an isotropic spatial correlation exists, the geometric mean would be the most appropriate (Matheron, 1963).

$$\text{Arithmetic\_mean} = \frac{1}{n}\sum_{i=1}^{n}\left(x_i\right) \qquad \text{Eq. 6-3a}$$

$$\text{Harmonic\_mean} = \left[\frac{1}{n}\sum_{i=1}^{n}\left(x_i^{-1}\right)\right]^{-1} \qquad \text{Eq. 6-3b}$$

$$\text{Geometric\_mean} = \sqrt[n]{x_1 \cdot x_2 \cdot x_3 \cdot x_4 \cdot \ldots \cdot x_n} \qquad \text{Eq. 6-3c}$$

A caveat: for some datasets (e.g., Schulze-Makuch et al., 1999 and some datasets in this study), the large-scale mean horizontal permeability may lie well above the arithmetic mean (or even maximum value) of support scale measurements. Clearly upscaling is not a trivial exercise and during field implementation of any design, one should undertake a formal program to evaluate all design parameters, including permeability at field scales.

6.6.2 Power law upscaling

The average (or effective) hydraulic conductivity based on upscaling has been investigated with considerable success by numerous authors using power law upscaling. Desbarats (1992) provides a development and summary of power law upscaling upon which the following is based. Because the application of power law scaling can be treated entirely empirically, few assumptions are needed, other than k_i is a stationary spatially random function at a particular scale (an element) and each element is assumed to be isotropic ($k_h = k_v$). (In most cases, neither of these assumptions will be true). While there is no theoretical basis for power averaging, there is good empirical agreement with field and analytical models and as Desbarats notes, it has the benefit of "usefulness and simplicity." A disadvantage is that it ignores the autocorrelation and inherent interconnectedness of higher permeability zones.

$$k_{\text{effective}} \approx k_{\text{average}} = \left(\frac{1}{V} \int_V (k_i)^p dV \right)^{\frac{1}{p}} \approx \left[\frac{1}{N} \sum_{i=1}^{N} k_i^p \right]^{\frac{1}{p}} \qquad \text{Eq. 6-4}$$

The averaging exponent, p, must be adjusted empirically (Deutsch, 1989) to fit the data. Matheron (1963) shows that p must lie between -1 and 1. For $p = -1$, the formula produces the harmonic mean; for $p \to 0$, the geometric mean results; for $p = 1$, it is the arithmetic mean. Desbarats (1992) indicates that for three-dimensional isotropic fields, $p \approx 1/3$. For anisotropic fields, where ($k_v = k_h/10$), the averaging exponent, p, for horizontal conductivity will be about 0.6 to 0.8 and for vertical, about –0.3 to –0.7.

To explore power averaging, three datasets were employed. Simulations using randomly sampled lognormally distributed data based on laboratory data ($v = 8 \times 10^{-4}\ m^3$, $N = 62$, $(\log k)_{avg} = -4.17$, $\log \sigma = 1.04$) and the standpipe slug test data ($v = 1 \times 10^{-2}\ m^3$, $N = 172$, $(\log k)_{avg} = -3.72$, $\log \sigma = 0.40$) were performed. For the purpose of this analysis, total variances (TE) are assumed to be due to natural variability (GE). Power law upscaling was applied over various volumes to upscale the data with various trial averaging exponents – a Monte Carlo analysis was used to generate 30 power-averaged permeabilities at each scale (simulating a recommended dataset size for a conventional design). The geometric mean of the 30 permeabilities at each scale is plotted in Figure 6-9A (for lab data) and Figure 6-9B (for standpipe data) for various p's to graphically determine the best fit to measured values. The vertical permeability on these graphs is estimated at 1/16 (scale independent) of the horizontal permeability based on traditional design practice in the oil sands region.

Based on the results in Figure 6-9A, upscaling from the laboratory data yields a modest fit using exponents of +0.8 and -0.25 for horizontal and vertical permeability, supporting in this instance, Desbarats' findings. Both the data and the power averaging indicate that the mean permeability remains essentially unchanged after reaching a volume of about 0.1 to 1.0 cubic metres.

However, power law scaling, based on the standpipe data (Figure 6-9B) was unable to recover the field mean, perhaps due to the poor assumption of homogeneity at this scale and that the arithmetic mean ($p = 1$) of the standpipe data is below the large-scale mean. Similarly, upscaling of surface tailings sand (from Figure 6-8B) was unsuccessful – even the arithmetic mean of 4×10^{-4} cm/s was below the large-scale mean (10^{-3} cm/s).

The above power law scaling provide some insight into permeability relationships, but perhaps not much design guidance for materials like tailings sand. Because the results are very sensitive to extreme values, the interpreted variance, and the values of the large scale permeability (horizontal and vertical), the use of power scaling for nearly homogeneous materials is perhaps of limited value to the practising engineer. Overall, it would seem that the scale effects of a homogeneous material such as tailings sand are more subtle than can be demonstrated with simple power law upscaling. Using Desbarats' values for p for tailings sand may or may not provide accurate results depending on the dataset employed.

6.7 Spatial variability

The study of spatial variability attempts to quantify the relationship of adjacent sample properties following Tobler's (1970) First Law of Geography, "Everything is related to everything else, but near things are more related than distant things."

There is a vast literature relating to spatial variability of soil properties. DeGroot and Baecher (1991) and DeGroot (1996) provide an overview of geotechnical aspects. The literature on spatial variability of hydraulic conductivity is rich and includes Delhomme (1979), Russo and Jury (1987a and 1987b), Peck and Bahr (1988), Wilson et al. (1989), Wollhiser et al. (1996), Mohanty et al. (1998a and 1998b) and Moustafa (2000).

Estimating the spatial variability is useful in several ways. It allows better definition of estimation of required sample spacing, size, or number, or an estimate of how far one can extrapolate a point value to adjacent areas (and hence may influence a sampling or testing program). It can also be used for further geostatistical analysis such as upscaling (allowing non-local techniques), kriging and distributed parameter watershed modelling.

6.7.1 Estimation methods

Two common methods used to describe spatial variability are autocorrelation and semivariance – equivalent for stationary random functions (Goovaerts, 1997). Both methods describe the variance of pairs of measurements and the average similarity of the data at different distances apart (the lag distance, h). Data may be in one, two, or three dimensions and may be equally spaced or clumped. Data in this chapter are based on one-dimensional data – lines of measurements.

To use autocorrelation or semivariance, the data must be stationary (i.e. they have has no overall spatial trend) and has a zero mean (DeGroot, 1996). This is usually accomplished by fitting the data with a trend line (or polynomial) and then analyzing the residuals from this line. Techniques for non-stationary functions are also available but are more complex.

Autocorrelation sums the products of values (k_i x k_j) whereas semivariance compares the squares of the differences $(k_i - k_j)^2$ where the ith and jth values are separated by some nominal lag, h. If the Data are clumped, it is first binned into class intervals of distance h before analysis. Ideally (but seldom practically) each bin should have more than 30 values to reduce scatter and aid in curve fitting.

The autocorrelation coefficient, also known as Moran's statistic, R(h), is given by the formula:

$$R(h) = \frac{1}{\sigma} \cdot \frac{1}{N(h)} \sum_{i=1}^{N(h)} \left[k_i \cdot k_{i+h}\right] \qquad \text{Eq. 6-5}$$

where N(h) is the number of observations at a given lag distance. The 1/σ term (where σ is the population variance at h = 0) normalizes values to between 1 and –1. The autocorrelation distance is defined as the distance, h, at which R(h) decays to 1/e ≈ 0.37 (DeGroot, 1996) and can be determined graphically when R(h) is plotted against h. At h = 0, R(h) is 1 (perfect self correlation). Where R(h) is zero, there is no correlation at this lag distance and thus can be called the zero correlation distance.

The semivariance, $\gamma(h)$ is given by:

$$\gamma(h) = \frac{1}{2 \cdot N(h)} \sum_{i=1}^{N(h)} \left(k_i - k_{i+h}\right)^2 \qquad \text{Eq. 6-6}$$

$\gamma(0)$ is often referred to as the nugget variance and this variance at zero lag is attributed to the combination of natural point to point variability (or "micro-variability") of the deposit (GE), errors in measurement (ME) and model error (AE). The plot of semivariance versus lag distance is called the semivariogram. The semivariance usually tends to increase to the population variance (σ) which is called the sill (or sill variance). The lag, h, at this distance is the range and is similar to the zero correlation distance.

For the tailings sand data, the semivariogram allowed a more transparent way of analyzing the data, provided an estimate of the nugget variance, a better estimate of the variance and range, and was more robust. This proved important when the lag internal was similar to the autocorrelation distance and when the number of data points for each lag was small. Most geostatistical software uses the semivariogram as an input function, but the geotechnical literature seems to favour autocorrelation.

6.7.2 Data gathering and analysis

Five datasets were gathered for analysis to demonstrate and estimate the spatial variability and in particular the autocorrelation distance and range of tailings sand permeability data. The relatively homogeneous nature of the tailings sand means that the overall variation in measurements is small.

Percolation data: As described in Section 6.3.5, two transects of surface percolation tests were run, each starting at the head of a beach, with 100 tests spaced at 1 m. Data were collected from two beaches (MLSB Cell 16 and 25) and are presented in Figure 6-10. The data were transformed using base 10 logarithm, and a small trend removed by subtracting a linear regression best-fit line. The residual data were used to generate an autocorrelation plot and a semivariogram using a 1-m lag spacing.

These figures indicate the autocorrelation distance is only 1.2 m and the range about 4 m. Both beaches gave essentially identical numbers. Thus characterization of an area through this test can only be extrapolated a very short distance. Similar findings of very small autocorrelation distances for infiltration into compacted clay liners was found by Benson (1991).

Standpipe data: Thirty-five standpipes were installed across a tailings sand beach at MLSB Cell 16. Installation of each standpipe was nearly identical with 1.3-m (vertical) completion zones and with the bottom of the screen at 3 m depth. Results are presented in Figure 6-11. The locations were clustered slightly with an average spacing of about 10 m. Data was binned to a constant spacing of about 4 m. Results are insensitive to the choice of lag spacing for this dataset.

The dataset has an autocorrelation distance of about 14 m and a range of about 75 to 125 m. That the autocorrelation distance is larger than that for the percolation data as would be expected owing to the ten-fold increase in test volume of an inhomogeneous material (Deutsch, 2001). The data shows a very narrow range of values at this site.

Whole-section back analysis: Seepage through 33 dyke cross-sections were back analyzed around the entire Mildred Lake Settling Basing ring dyke (see Figure 6-1) using Seep/W as described above. The dyke perimeter (measured at the downstream crest) is 18 000 m. The average cross-section spacing was 550 m which was used as the lag (and for binning).

Spatial variability results are presented in Figure 6-12. The measured autocorrelation distance of 700 m was only slightly greater than the average spacing, but is generally supported by the 5000-m range measured with the semivariogram.

One should note that the autocorrelation distance of the back-analyzed sections may relate less to the true autocorrelation of permeability and more to the analysis as a whole – the correlation of different geometry and geology (boundary conditions) for the various sections are inseparable from the permeability autocorrelation. In other words, the correlation distance is not entirely an intrinsic property of the material, but includes the test and analysis method (Long, 1998; Western and Bloeschl, 1999) and is discussed in more detail below.

Cone penetration resistance: There are no data with which to calculate the vertical spatial variability of vertical tailings sand permeability. However, one may be able to crudely estimate small-scale variability by analyzing cone tip resistance as a surrogate. Data from Syncrude tailings sand (Figure 6-13) reveals a vertical autocorrelation distance of about 0.2 m and a range of 0.3 m, which probably corresponds to typical bed thicknesses. Figure 6-14 provides scatterplots of these data to better illustrate autocorrelation coefficients. Because cone data are collected at small constant intervals and available in electronic form, these are particularly easy to analyze. Similar analysis of sleeve resistance, pore-pressure response, and time domain reflectometry data from the same and other coneholes provides similar autocorrelation distances. It seems likely that vertical permeability would have similar or smaller autocorrelation distances at this measurement scale. Active and passive gamma measurements that test a larger sample volume provided larger autocorrelation distances, as might be expected.

6.7.3 Spatial data summary

Table 6-2 summarizes the spatial data. The two autocorrelation methods provide similar results and the choice of method is one of convenience. While it is unfortunate that there are no data of intermediate scale, data from three available scales show the autocorrelation distance (and range) is a function of the test volume as would be expected due to nesting of scales of permeability (from the millimetre sand/silt laminate, to bed thickness, lift heights, and laterally to include meandering channels). One result of nested scales is the appearance of multiple sills on semivariograms (for example, Figure 6-13). The degree to which the test and analysis methods affect the autocorrelation are uncertain, but important for relatively homogeneous materials like tailings sand.

Autocorrelation distances reported here are similar to those reported by DeGroot (1996, Table 2) for in situ geotechnical strength tests. Autocorrelation distances for small-scale geotechnical tests are often in the 3 to 10 m range (horizontally) and about 1/10 that value vertically. The effect of scale on autocorrelation distance (and in particular the effect of the scale of the measurement data relative to the periodicity of various nested scales) does not appear to be formally addressed in geotechnical literature (perhaps since most tests are taken at a similar (small) scale). The geostatistical literature deals with the effect of scale on the nugget effect (e.g., Journel and Huijbregts, 1981) but less obviously with its effect on the autocorrelation distance. Scale effects on autocorrelation distance, however, are presently a popular topic in the landscape ecology literature, especially as they relate to vegetation patch distribution at field mapping versus coarse-grained satellite imagery scales (e.g., Nikora et al., 1999).

6.8 Worked example

This section demonstrates the use of geostatistics in landscape engineering using a simple example from the oil sands region. Approximately 6000 hectares of Syncrude's Mildred Lake landscape will consist of tailings sand blankets overlying soft tailings deposits. This blanket must be designed to provide good short- and long term trafficability, control waterlogging and salinization of reclamation soils, and be economical to place. Both calculation and local experience indicate the need to control long term water tables in the sand caps so that they remain at safe depth below the ground surface.

The design question answered in this section is as follows: "For a 6-m thick tailings sand blanket, what spacing of 4-m deep drains (swales, ditches, or buried slotted pipe) is required to keep the long term water table 2 m below the tailings sand surface?" For the purpose of this example, the models are assumed accurate, and all but two variables fixed: the tailings sand horizontal hydraulic conductivity and the precipitation percolation rate (expressed as a percent of 450 mm of average annual precipitation). It is assumed that the steady state Dupuit-Forchheimer (Kirkham, 1967) equation is applicable:

$$h_{max}^2 = h_d^2 + \frac{e}{k_h} \cdot \frac{L^2}{4} \qquad \text{Eq. 6-7}$$

where h_{max} is the maximum height of the water table above the base of the unconfined aquifer between drains separated by a distance, L. The head at the drain invert is h_d, e is the estimated annual percolation rate (with the same units as permeability and based on previous studies), and k_h is the effective horizontal hydraulic conductivity. For the case of a 6-m thick aquifer with 4-m deep drains and a water table no closer than 2 m to the ground surface, $h_{max} \leq 4$ m, $h_d = 2$ m and hence:

$$L \leq \sqrt{48\frac{k_h}{e}} \qquad \text{Eq. 6-8}$$

Table 6-4 provides a summary of the maximum drain spacing based on the various methods described below. The design range shown is a subjective evaluation of realistic drain spacings based on data available from that particular methods. The last section provides an overall comment and planned direction at Syncrude.

Extrapolation of historical experience

An initial spacing for the ridge and swale topography planned for sand capped soft tailings was needed for conceptual closure designs several years ago. The spacing of 200 to 500 m was chosen based on previous experience with subsurface drainage in sandy soils in agricultural areas for 5-m deep drains (Sawatsky, 2001). For 4-m deep swales in the present example, this range is approximately 200 to 400 m. (Analysis below generally confirms this experiential estimate).

Upscaling using 85th percentile rule

The 85th percentile of all laboratory permeability data are 6.3 x 10^{-4} cm/s. Ten randomly selected values from this database (meant to simulate the situation where only 10 datapoints are available to the designer) are shown in Table 6-5. The 85th percentile of this small sample is 2.0 x 10^{-3} cm/s which is much higher owing to several of the highest permeability values being randomly selected. (A 75th percentile values in this case would have provided more accurate results and indicates that perhaps a larger number of samples (20 to 30) would provide a lower probability of over or underestimating a more typical value). The results show a high expected drain spacing, a wide range of possible values, and a design range of 100 to 500 m. One would probably chose a value towards the conservative end of the spectrum given the uncertainty in this method.

The 85th percentile of all field slug test data are 4.2 x 10^{-4} cm/s. Ten randomly selected values from this database are shown in Table 6-5. The 85th percentile of this small sample is 3.2 x 10^{-4} cm/s. The results show an expected drain spacing of 230 m with a design range of 150 to 250 m.

Prediction based on back analysis using finite element

A common and powerful approach to design of dykes and other landforms is to calibrate a numerical seepage model by back analyzing a similar field condition (or analog), then using this model for predicting seepage under various design and operational scenarios. The Syncrude Mildred Lake Bison Ranch pasture on reclaimed land offers a useful analog. It is located on a 10-m thick, 500-m wide tailings sand toe berm that has 10-m deep drains at either side and is capped with coversoil and pasture grass. Before reclamation, when the surface of this area was bare tailings sand, the water table was near the surface over most of the area. After coversoil placement, the watertable dropped to a relatively uniform and constant 5m depth. Back analysis of this condition using Seep/W (a two-dimensional finite element groundwater / seepage program) provides a suite of solutions with a constant ratio of percolation to permeability e/k_h = 2400 (there is no measure of flux rates, so a unique e-k_h couplet cannot be determined). One might estimate that this is equivalent to a percolation value of 10% and a hydraulic conductivity of 3.5×10^{-4} cm/s. Extrapolation to the example design results in 240 m drain spacing with a design range of 200 to 300 m.

Prediction based on back analysis using DF equation

Use of a Dupuit-Forchheimer equation for back analysis of the bison pasture described above provided nearly identical conditions and predictions as the finite element method (but is much faster and more amenable to probabilistic analysis.)

Power-law upscaling

Power-law upscaling of the 10 laboratory datapoints in Table 6-6 using a scaling exponent of $p=0.8$ resulted in an upscaled hydraulic conductivity of 4.0×10^{-3} cm/s which is high and would result in an expected drain spacing value of 800 m.

Power-law upscaling using the ten standpipe slug test datapoints resulted in a hydraulic conductivity of 2.5×10^{-4} cm/s and an expected drain spacing of 200 m. This match seems more reasonable than that of the laboratory data, but is perhaps merely fortuitous.

Permeability estimated from grain-size data

Hazen (1911) suggests an empirical relationship between the d_{10} value (the 10th percentile grain-size diameter) for silty sands and permeability. When the grain size is measured in millimetres and the permeability in centimetres per second, the relationship is $k = d_{10}^2$ (Freeze and Cherry, 1979). Previous analyses at Syncrude indicate that for oil sand tailings sand, the Hazen formula tends to systematically overpredict the horizontal permeability by a factor of about 10, likely due to the nearly complete dispersion of the fines in oil sands tailings sand. This approach also overlooks scale effects and the fact that there is generally several orders of magnitude of scatter above and below the predicted line. Regardless, using the original relationship, a permeability of 3.6 x 10^{-3} cm/s results in an expected drain spacing of 780 m. Applying some conservatism in design, a design range of 200 to 400 m would be selected. Using the proposed modified Hazen formulation ($k=d_{10}^2/10$), the permeability is 4.4 x 10^{-4} cm/s, the expected drain spacing is 270 m with a design range of 100 to 300 m. Many other empirical formulae are also available, but are likely also of limited use for design.

SCL dyke design values

The present tailings sand horizontal permeability value employed at Syncrude is 8 x 10^{-4} cm/s with sensitivity checks at 10^{-4} cm/s and 10^{-3} cm/s for dyke designs. Use of this value results in an expected drain spacing of 370 m with a design range of 200 to 500 m.

Design using probability of success / Monte Carlo

A Monte Carlo analysis using n=10,000 runs was performed using the DF equation and using a log normal distribution of permeability values based on large-scale dyke back analysis with a mean of -3.32 (4.8 x 10^{-4} cm/s) and a coefficient of variation of 11%. The deep percolation coefficient, i, was assumed to have a normal distribution with a mean of 20% with a coefficient of variation of 20% (giving the percolation value in the simulation a range from about 10 to 30%). For simplicity, the permeability and the percolation were assumed to be uncorrelated in the simulation – arguing that the upper tailings sand layer of higher permeability likely reduces their correlation. Other parameters (such as drain depth and aquifer thickness) were assumed constant and defined. For each couplet of permeability and percolation, and for a given length, the combination is considered "successful" if the steady state watertable is less than 2 m below the sand surface. The probability of success is defined as the ratio of the number of trials that are successful to the total number of runs. Figure 6-15 shows that at a drain spacing of 100 m, about 99% of all combinations of permeability and percolation are successful, but this drops rapidly and by 400 m spacing, only 20% of cases are predicted to provide success. For mine reclamation, if the cost of failure is not great, one might choose for 75 to 90 percent success and might target a swale spacing of 150 to 200 m. (Before implementation, a slightly more involved analysis that included further deep percolation modelling, perhaps measurements using several lysimeters, and considerations of other uncertainties would be performed.)

Cost/risk benefit analysis example

While there are many good books on subsurface drainage (e.g., van Schilfgaarde, 1974; Luthin, 1978; ASCE, 1998) that provide analytical methods and supporting test procedures, most small subsurface drainage design follows a simple method. A shrewd farmer, having made the decision to lower the water table to his (or her) land to improve crop yields, looks at the spacing used by his neighbours. In most cases, the farmer will be willing to take some risk, and so will use a wider spacing (thus potentially saving considerable money) knowing that if results warrant, that additional pipes or ditching may be required in some areas, effectively "splitting the difference" by halving the spacing in some or most of the interdrain zones. In many cases, the unit cost of retrofitting is similar to that of the original installation. Some costs in terms of lost production between installation of the primary and secondary drains may also be incurred.

A simple cost-benefit analysis was performed to examine the merits of installing drains in stages for reclamation purposes on a large tailings sand plateau. The analysis attempts to answer the question, "What is the optimum initial drain spacing?" recognizing that future drains could be installed if performance warrants. Indeed, if even under this secondary installation, if areas are still failing, tertiary drains could be installed.

In this particular analysis, it assumes that all areas pass or all area fail. The secondary drainage schemes halves the initial spacing by doubling the number of drains. This is essentially a form of Baynesian updating or the observational method (Peck, 1969). The tertiary drainage schemes halve the spacing again by quadrupling the number of drains. The expected value is the initial cost of drains (expressed on a dollars per hectare basis) plus the cost of secondary drainage multiplied by the probability of failure of the primary drains, and so on. The same distributions of permeability and percolation described above were employed.

The optimum initial spacing is a function of the ratio, R, of the unit cost of secondary and tertiary drains versus the primary ones. For the case where the costs are similar (R=1), the optimum initial spacing is 150 to 300 m and roughly corresponds to the strategy of the shrewd farmer. In some cases, the costs of installing the secondary drainage is less than that of the primary (R<1), perhaps due to easier installation due to partial lowering of the water table by the primary drainage, and perhaps due to discounting of future expenses by the mine (time value of money). In the case where R=0.5, the initial drain spacing is somewhat greater than 250 m. This strategy has the additional benefit that not all areas would need the secondary or tertiary drainage schemes. Most commonly, secondary drainage unit costs will be at least a little greater than the primary (R>1). If the incremental costs are marginal, initial spacings of 175 m are indicated. If costs are much greater (say R>5), then one would wish to get it right the first time, and spacings of 100 m are appropriate.

Discussion

The cost-risk benefit methodology supports the earlier methods – one would use the lower end of the range if the cost of failure (delays in satisfying goals plus retrofit costs) are high and the higher end of the ranges if retrofitting costs are low.

Each of the ranges provided by each of the methods is fairly similar, but only if judgement is applied to the results. Reliance on lab samples may lead to erroneous results if an insufficient number of samples are taken. Failure to upscale permeability values may also lead to adoptions of permeability that are too small and drain spacing that is unnecessarily close and expensive.

Different areas of the beach will exhibit different permeabilities and infiltration rates, just through the random nature of the material properties of the cover and tailings. A variety of performance should be expected and encouraged in the name of diversity and economy. The ideal situation would be to construct swales at a variety of spacings and monitor performance as the vegetation develops. Goals for long term performance could be set so that some areas could be allowed to have higher water tables. Those areas still showing unacceptable performance would be retrofit with additional drainage measures.

Confidence is highest with those methods based on back analysis. Indeed, the preferred course of action is to use such an analysis to bracket the answers (in this case, spacing of 100 to 300 m) and, like the shrewd farmer, test the upper end of the range with several well monitored prototypes, keeping track of the resulting groundwater flow patterns spatially and temporally. Learnings from construction of the swale and ridge topography on one landform can be applied to others, provided it is supported with just enough monitoring and testing, so that future areas can be designed more cheaply, with less conservatism, and perhaps requiring less retrofitting of problem areas.

From the work above, it is also recognized that the permeability is not constant in each interdrain zone, but varies spatially up, down, and within each beach. The use of the semivariogram and stochastic models could be employed to better estimate the distribution of water table locations in two and three dimensions to predict not whether each interdrain zone fails at a single location, but the aerial extent of any high water tables. Whether this type of effort is justified likely depends on the costs of providing adequate water table control and the consequences of failure – in most landscape engineering situations, semivariograms and autocorrelation distances are best limited to providing designers with a better understanding of deposit variability.

6.9 Summary and conclusions

Specific to Syncrude oil sand tailings sand

Values of permeability of Syncrude oil sands tailings sand have been gathered into a database of unusual size. Test volumes span 11 orders of magnitude and permeabilities span 7. Near surface (say top 1 m) of tailings sand seems to exhibit isotropic behaviour and has a slightly higher permeability than deeper sand and can be considered a separate population. Statistical distributions for each method (and hence each scale) are positively skewed and are approximately lognormal as is common for hydraulic conductivity data.

The coefficients of variation of permeability from the test methods are similar to those in the geotechnical framework of Phoon and Kulhawy (1999b) and typically ranges from about 10 to 25 percent (for log transformed data with hydraulic conductivity units of cm/s) which is similar to that of other (non log-transformed) geotechnical properties and slightly higher than those calculated from some other hydraulic conductivity data. Perhaps unexpected, the coefficient of variation (or variance in general) does not seem to necessarily decrease with scale. The true geological coefficient of variation is some fraction of the total coefficient of variation that includes experimental and model error – non-geological error is roughly estimated at +/- half an order of magnitude for most tests methods.

Based on this study for large dykes, an average value for horizontal permeability (k_h) is interpreted 5 x 10^{-4} cm/s. Recognition of a range of values of about +/- a half order of magnitude (10^{-4} to 10^{-3} cm/s) is needed in design. The traditional oil sands permeability ratio (k_h/k_v) of 16 for dyke seepage analysis lies within the typical range of 1 to 20 from back-analysis and while not confirmed, could not be improved upon except to suggest a slightly lower value of 10 which implies less precision. One should recognize that this ratio is likely scale dependent and has its own statistical distribution. Surface tailings sand is interpreted to have an average permeability of 10^{-3} cm/s and is perhaps, on average, isotropic.

Tailings sand permeability seems to exhibit scale relations that seem to be on the boundary between homogeneous and heterogeneous porous flow materials as classified by Schulze-Makuch et al. (1999). At test volumes about $0.1\mathrm{m}^3$, the mean permeability is scale invariant. This large-scale permeability is equivalent to the 85th percentile of both laboratory permeability and field standpipe slug test values. Other more complex upscaling techniques may provide some insight but little numerical guidance for practitioners, perhaps due to the relatively homogenous nature of oil sand tailings sand.

Autocorrelation diagrams and semivariograms for spatial variability are easily calculated. Surface percolation tests have horizontal autocorrelation distance of about 1 m, standpipes of about 15 m and dyke cross-sections about 700 m. (The equivalent semivariogram ranges are 4 m, 75 m, and 5000 m respectively). Small-scale vertical autocorrelation distances are crudely estimated to be about 20 cm based on cone penetration values. Autocorrelation distances seem to be a function of scale and test method, an outcome that if not novel, may be underappreciated. In particular, for geotechnical work, recognition that the autocorrelation distance is not solely function of the deposit and its description (and use) must be quantified with a description of the method and dimensions of the test.

Further testing seems unlikely to shed additional information on the permeability of Syncrude oil sand tailings sand, other than perhaps allowing the relative contribution of geologic and non-geologic errors as a proportion of variance (or coefficient of variation) to be better estimated. Remaining uncertainty is left to sensitivity or probabilistic treatment in design.

A simplified analysis of drain spacing for sand capped soft tailings suggests that most of the geostatistical methods provide reasonable initial design parameters for choosing economic drain spacing. Using the shrewd farmer's method of picking an optimistically large spacing and being prepared to retrofit areas with high water tables (by splitting the difference with additional drains) is a sound strategy provided the unit costs for retrofitting are not too high relative to that of the primary drainage, and there is regulatory acceptance for use of the observational method. Initial drain spacing of 100 to 300 m is recommended (for the geometry analyzed) and the use of an instrumented prototype would help to reduce the uncertainty and narrow the range.

General conclusions

Practitioners should recognize that many parameters that are often taken as deterministic exhibit scale and spatial variability.

In addition to permeability, which is shown above to exhibit variability spatially as well as with scale, other parameters of importance to landscape engineers should be viewed in a similar light. Flushing rates based on laboratory tests may not mimic rates or processes at larger scales in the field, especially where preferential flow dominates. Similarly, soil-water retention curves, unsaturated permeability, and deep percolation (groundwater recharge) through cover materials all exhibit scale and spatial variability. This variability should be acknowledged in analysis. Simplifying assumptions will be required to incorporate this variability into landscape design.

There is enough natural variability in the samples, particularly at the laboratory scale, that any laboratory tests for measuring effects of subtle differences in samples need to be carefully designed and have enough samples for statistically valid results. Transferring conclusions to the field should take into account explicit upscaling. Field scale testing to confirm laboratory results is usually needed.

Perhaps the most important conclusion is that even with extensive testing and analytical efforts, large-scale permeability can only be estimated to within +/- a half order of magnitude even for a rather homogenous, as-built, artificial material like oil sand tailings sand. Testing and designs need to account for local variability at small scale, and uncertainty at large scale, by employing conservatism in design, and where possible, the ability to modify designs if unacceptable performance is discovered.

To take into account variability more transparently, especially for dealing with technically oriented reviewers, managers, and regulators, simple probability-based designs should be considered. Means and variances can be used in simplified Monte Carlo analysis to estimate fluxes and water table locations, and to evaluate economics of various scenarios, especially ones that reduce the initial capital with the ability to modify designs as information becomes available, using the observational method (Peck, 1969; Morgenstern, 1994; Institution of Civil Engineers, 1996) where practical and acceptable. This approach can complement the existing method of choosing deterministic values and doing sensitivity analyses.

A simple framework of describing means, coefficients of variation, scale variability, and spatial variability is presented that can be used to describe other materials (such as other tailings, waste rock or overburden dumps, cover soils, and undisturbed) in landscape engineering.

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Table 6-1 Statistical summary of permeability tests

Test type	n	Test volume (m^3)	Generalized range k_h (cm/s)	Raw hydraulic conductive data (cm/s)				Log transform of permeability data (log cm/s)			
				Avg	σ^2	σ	COV[a] %	Avg	σ^2	σ	CoV[a] %
All data	829	10^{-4} to 10^{+7}	10^{-7} to 10^{-2}	$1.9x10^{-3}$	$3.6x10^{-5}$	$6.0x10^{-3}$	319	-3.30	0.71	0.85	26
Lab frozen core	*23*	10^{-4}	10^{-5} *to* 10^{-3}	$3.5x10^{-4}$	$8.6x10^{-8}$	$2.9x10^{-4}$	*84*	*-3.65*	*0.21*	*0.46*	*13*
Field percolation	*199*	10^{-3}	10^{-3} *to* 10^{-2}	$4.5x10^{-3}$	$8.0x10^{-6}$	$2.8x10^{-3}$	*63*	*-2.48*	*0.16*	*0.41*	*16*
Field Guelph permea-meter	*26*	$5 x 10^{-3}$	10^{-4} *to* 10^{-2}	$1.2x10^{-3}$	$1.0x10^{-6}$	$1.0x10^{-3}$	*88*	*-3.11*	*0.16*	*0.41*	*13*
Field infiltration	*30*	10^{-2}	10^{-4} *to* 10^{-2}	$1.7x10^{-3}$	$2.8x10^{-6}$	$1.7x10^{-3}$	*99*	*-3.08*	*0.39*	*0.63*	*20*
Lab reconstituted	16	10^{-3}	10^{-5} to 10^{-3}	$2.2x10^{-4}$	$9.3x10^{-8}$	$3.0x10^{-4}$	136	-3.96	0.28	0.53	13
Lab undiff-erentiated	43	10^{-3}	10^{-7} to 10^{-3}	$2.7x10^{-4}$	$3.9x10^{-7}$	$6.2x10^{-4}$	232	-4.52	1.57	1.25	28
Field stand-pipe slug	172	10^{-2}	10^{-5} to 10^{-3}	$2.9x10^{-4}$	$2.3x10^{-7}$	$4.8x10^{-4}$	167	-3.72	0.16	0.40	11
Lab model	6	10^{-1}	10^{-3} to 10^{-2}	$2.3x10^{-3}$	$4.7x10^{-6}$	$2.2x10^{-3}$	96	-2.79	0.11	0.33	12
Field con-solidation	10	10^{+1}	10^{-6} to 10^{-4}	$3.8x10^{-5}$	$1.4x10^{-9}$	$3.8x10^{-5}$	101	-4.69	0.33	0.57	12
Field pump	26	10^{+3}	10^{-4} to 10^{-3}	$5.8x10^{-4}$	$4.8x10^{-8}$	$2.2x10^{-4}$	38	-3.27	0.02	0.16	5
Field gradient	229	10^{+2} to 10^{+7}	10^{-4} to 10^{-2}	$2.1x10^{-3}$	$1.2x10^{-4}$	$1.1x10^{-2}$	513	-3.23	0.29	0.54	17
Field dyke back analysis	37	10^{+6} to 10^{+7}	10^{-4} to 10^{-3}	$5.8x10^{-4}$	$3.3x10^{-7}$	$5.8x10^{-4}$	99	-3.36	0.10	0.32	10
Field dyke back analysis (historical)	7	10^{+6} to 10^{+7}	10^{-4} to 10^{-3}	$1.2x10^{-3}$	$6.0x10^{-7}$	$7.8x10^{-4}$	65	-3.11	0.24	0.49	16
All lab	82			$2.8x10^{-4}$	$2.5x10^{-7}$	$5.0x10^{-4}$	176	-4.17	1.08	1.04	25
All infiltration	*56*			$1.4x10^{-3}$	$2.0x10^{-6}$	$1.4x10^{-3}$	*99*	*-3.09*	*0.29*	*0.54*	*17*
All dyke back analysis	44			$6.8x10^{-4}$	$4.2x10^{-7}$	$6.5x10^{-4}$	96	-3.32	0.13	0.36	11

[a] CoV = Coefficient of variance = coefficient of variation = standard deviation / mean = σ / Avg. Coefficients of variation of log transformed distributions are sensitive to the units and base of the logarithm. In the case of the final column, base 10 logarithms are used to cover permeability data with units of cm/s.

Italicized text indicates surface beach samples (low confining stress)

Table 6-2 Summary of spatial variability statistics

Dataset	Test volume (m^3)	Autocorrelation distance (m)	Range (m)	Nugget variance	Sill variance
Percolation Cell 16	2×10^{-3}	1.2	4	0.034	0.06
Percolation Cell 25	2×10^{-3}	1.2	4	0.027	0.04
Standpipes	2×10^{-2}	14	75-125	0.007	0.03
Dyke section	7×10^{6}	700	5000	0.060	0.14
Cone – tip resistance (vertical)	1×10^{-4}	0.2	0.3		
See text for definitions.					

Table 6-3 Comparison of scale coefficients to published values

Material type	Geological unit	N	Scaling Exponent m	Scaling coefficient c m/s	Upper-bound scale, vL m^3
Homo-geneous	Brent group (sandstone)	3008	>0.19		$<10^{-5}$
	St Peter – Wisconsin (sandstone)	257		2×10^{-5}	$<10^{-5}$
	St Peter – Chicago (sandstone)	24		3×10^{-7}	
	St Peter Fm (sandstone)	305		10^{-3}	
	Dresback Fm (sandstone)	40	0.65	10^{-3}	
	Mt Simon Fm (sandstone)	151		10^{-4}	
	Syncrude surface tailings (sand)	**85**	**0.40**	$\mathbf{10^{-4}}$	$\mathbf{10^{-3}}$
	Syncrude tailings (sand)	**540**	**0.40**	$\mathbf{10^{-5}}$	$\mathbf{10^{-1}}$
Hetero-geneous porous-flow	Edgewood formation (dolostone)	84	0.49	1.6×10^{-8}	$>10^{0}$
	Reef carbonate (boundstone)	65	0.45	2.5×10^{-6}	$>10^{2}$
	Glaciolacustrine sediments (stratified sand, silt, and clay)	49	0.48	2.0×10^{-6}	$>10^{2}$
	Alluvium (stratified sand)	48	0.50	1.6×10^{-5}	$>10^{3}$
	Franconia / Lone Rock Fm (clastics and dolostone)	22	0.52	7.9×10^{-6}	10^{2}-10^{3}
	Glacial outwash sediments (sand and gravel)	49	0.53	3.2×10^{-5}	10^{3}-10^{4}
	Theinsville Fm (clastics and dolostone)	190	0.52	2.0×10^{-6}	10^{3}-10^{4}
	Mayville Fm (vuggy dolostone)	104	0.55	2.5×10^{-7}	10^{4}-10^{5}
Summary values					
Homogeneous media			>0.19-0.65		$<10^{0}$
Heterogeneous porous flow media			0.45-0.55	2×10^{-8} - 3×10^{-5}	$>10^{0}$ - 10^{5}
Double-porosity media			0.55-0.83	3×10^{-8} - 1×10^{-5}	$>10^{1}$-10^{6}
Fracture-flow media			0.80-1.13	3×10^{-9} - 6×10^{-7}	10^{0}-10^{4}
Conduit-flow media			0.67-1.11	2×10^{-9} - 2×10^{-6}	$>10^{3}$->10^{9}

Table adapted from Schulze-Makuch et al. (1999)

Table 6-4 Water table control design drain spacing based on various geostatistical methods

	Expected tailings sand permeability (cm/s) (range in brackets)	Maximum drain spacing (m)							
		Lower bound L	Lower bound k	Upper bound i	Expected value	Lowe bound i	Upper bound k	Upper bound L	Design range
1. Extrapolation of historical experience									**200-400**
2. Lab - 85th percentile	2.0×10^{-3} (9.6×10^{-5} to 7.0×10^{-3})	5	5	100	**580**	820	1100	1500	**100-500**
3. Slug – 85th percentile	3.2×10^{-4} (1.2×10^{-5} to 3.6×10^{-4})	40	45	190	**230**	330	250	350	**150-250**
4. Seep/W back analysis	3.5×10^{-4} (2.0×10^{-4} to 7.0×10^{-4})	150	180	200	**240**	340	340	480	**200-300**
5. DF back analysis	3.6×10^{-4} (1.8×10^{-4} to 7.1×10^{-4})	140	180	200	**240**	350	350	490	**200-300**
6. Power law, lab data	4.0×10^{-3}				**800**				
7. Power law, slug data	2.5×10^{-4}				**200**				
8. Hazen D10	3.6×10^{-3} (4.0×10^{-4} to 4.9×10^{-3})	210	260	640	**780**	1100	910	1300	**200-400**
9. Hazen D10/10	4.4×10^{-4} (4.0×10^{-5} to 4.9×10^{-4})	65	80	200	**270**	350	290	410	**100-300**
10. SCL Dyke Design	8.0×10^{-4} (1.0×10^{-4} to 1.0×10^{-3})	110	230	300	**370**	520	410	580	**200-500**
11. Probability of success*	99 %								**100**
	90 %								**165**
	75 %								**215**
	50 %								**280**
	25 %								**380**
12. Cost/risk benefit*	Retrofit / built in drainage cost ratio = 0.5								**300**
	Retrofit / built in drainage cost ratio = 1								**150-300**
	Retrofit / built in drainage cost ratio = 2								**125-175**
	Retrofit / built in drainage cost ratio = 5								**100-130**

**Assumes average long term deep percolation rate is most likely 20% of annual precipitation (450mm) for forested reclaimed tailings sand with water table at least 2m below ground surface. For sensitivity analyses i = 10% and 30% were as lower and upper bounds. For probabilistic analysis, a normal distribution of percolation rates was used with a 20 percent mean and standard deviation of 4 percentage points.*

Table 6-5 Details of subsample of slug test and laboratory test permeability data used for worked example

	Slug	Laboratory
Number of tests in database	175	79
Number of tests in random subsample	10	10
85th percentile permeability of tests in database	4.2×10^{-4}	6.3×10^{-4}
85th percentile permeability of subsample	3.2×10^{-4}	2.0×10^{-3}
Mean of log transform permeability values (geometric mean) of subsample	-3.76 (1.8×10^{-4})	-4.02 (9.5×10^{-5})
Standard deviation of log transform values from subsample	0.425	1.31
Coefficient of variation (CoV)	11.3%	32.6%
Values from random subsample	1.2×10^{-5}	2.9×10^{-7}
	1.3×10^{-4}	7.5×10^{-6}
	1.7×10^{-4}	1.5×10^{-5}
	2.0×10^{-4}	4.0×10^{-5}
	2.2×10^{-4}	6.4×10^{-5}
	2.3×10^{-4}	1.2×10^{-4}
	2.7×10^{-4}	2.2×10^{-4}
	3.0×10^{-4}	2.0×10^{-3}
	3.3×10^{-4}	2.0×10^{-3}
	3.6×10^{-4}	7.0×10^{-3}

Figure 6-1 Study area: Syncrude's Mildred Lake Operation in 2001. (False-colour satellite image shows an area approximately 24km x 28km.) Syncrude's Mildred Lake Settling Basin (MLSB) is visible near the top of the photograph and the Southwest Sand Storage Facility (SWSS) is visible at the left edge.

Figure 6-2 **Oil sand tailings sand grain-size curves**

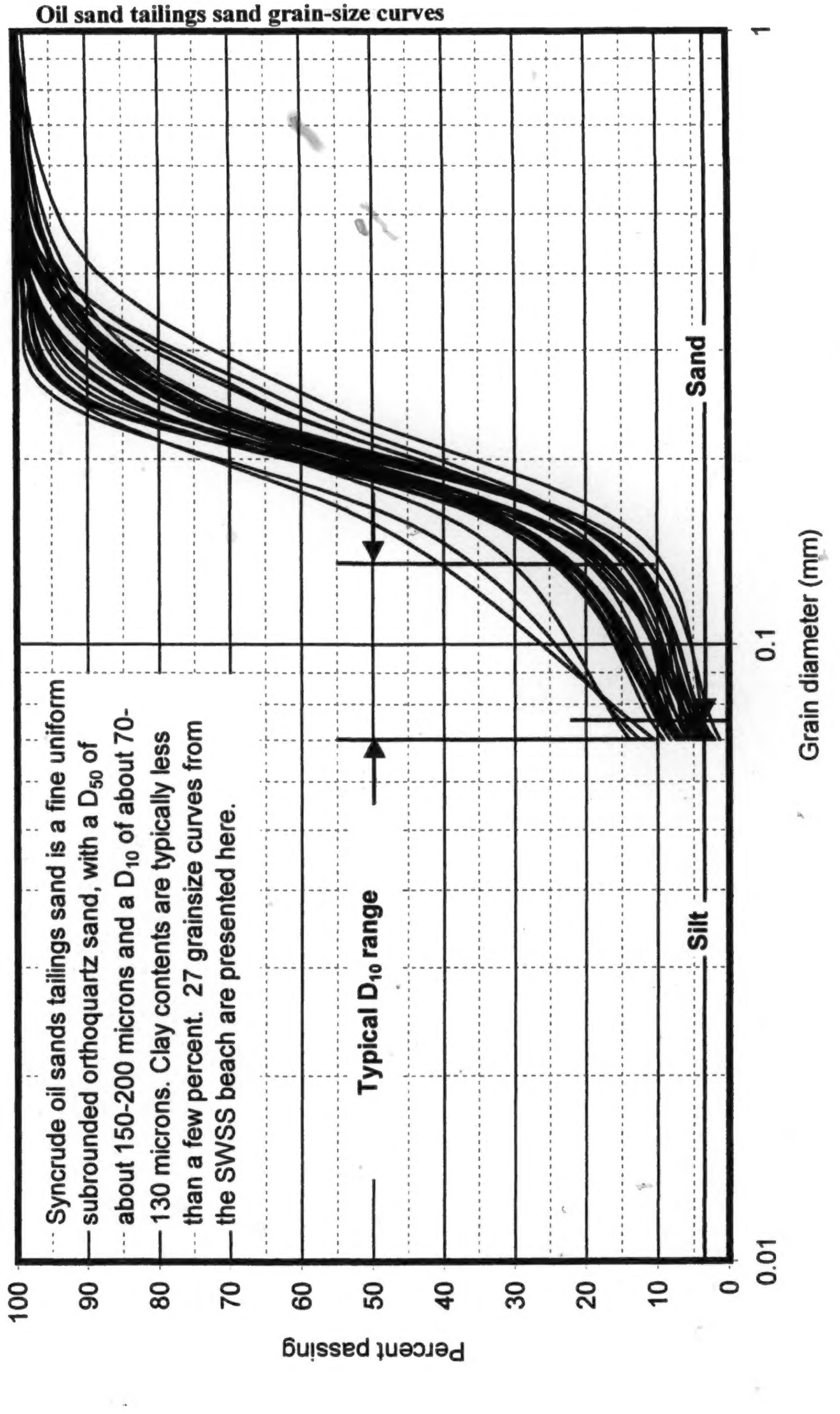
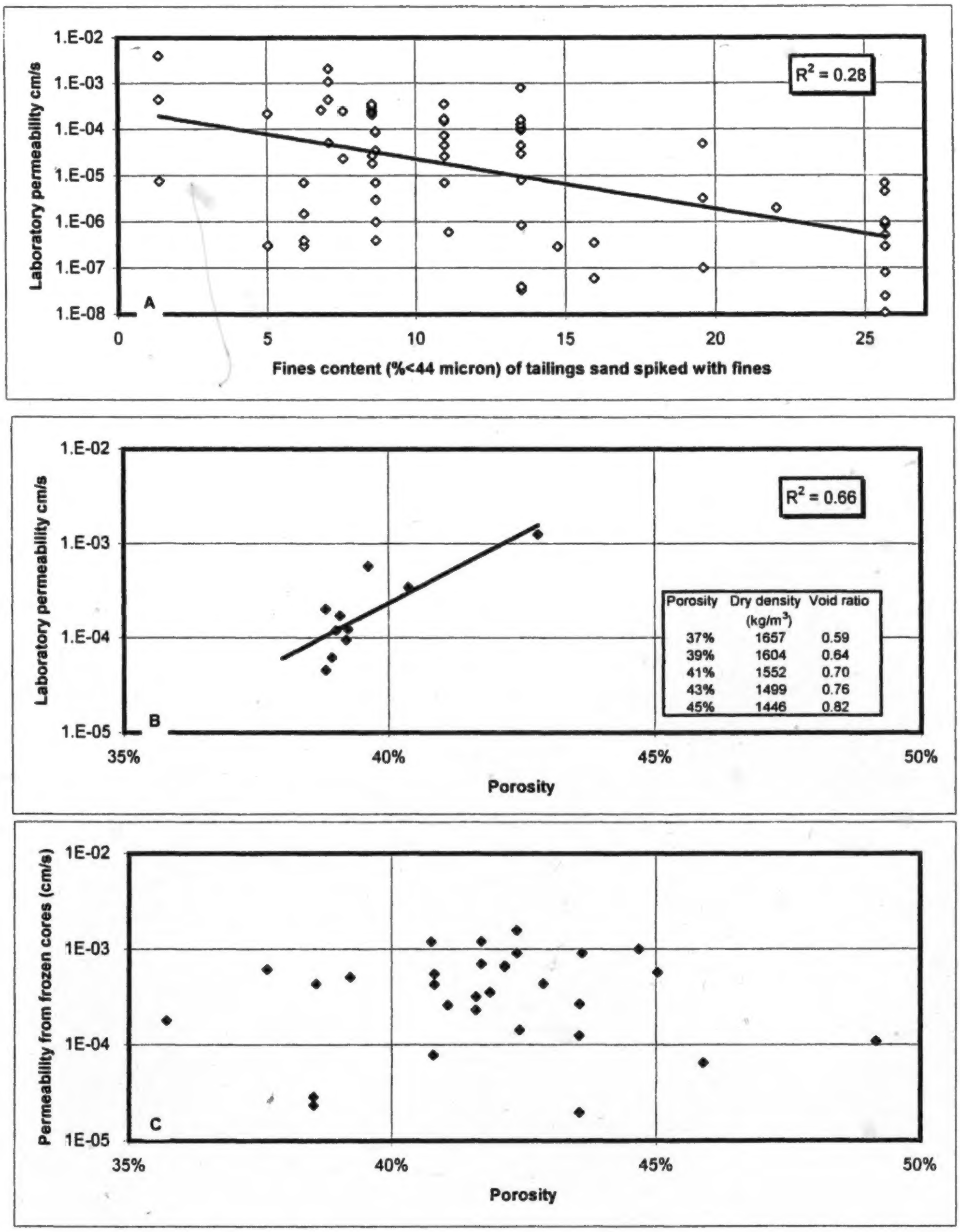


Figure 6-3 Relationship of density and fines content to permeability of Syncrude oil sand tailings sand. Figure 6-3A shows the effect of spiking tailings sand with fines (mature fine tailings) and the scatter that results. Figure 6-3B shows the effect of compaction on a uniform sample of tailing sand tested in the lab. Figure 6-3C shows the apparent insensitivity of permeability to the porosity of naturally frozen surface samples of tailings sand.



Porosity	Dry density (kg/m³)	Void ratio
37%	1657	0.59
39%	1604	0.64
41%	1552	0.70
43%	1499	0.76
45%	1446	0.82

Figure 6-4 **Distribution of tailings sand permeability from 172 slug tests. Figure 6-4A shows an arithmetic histogram of raw permeability data. Figure 6-4B shows log transformed data. Figure 6-4C shows the data using a probability plot and compares the distribution of dyke seepage back analysis at field scales – the straight lines on this plot show the goodness of fit to lognormal distributions. The x-axis in each is the log of the permeability (in units of log cm/s).**

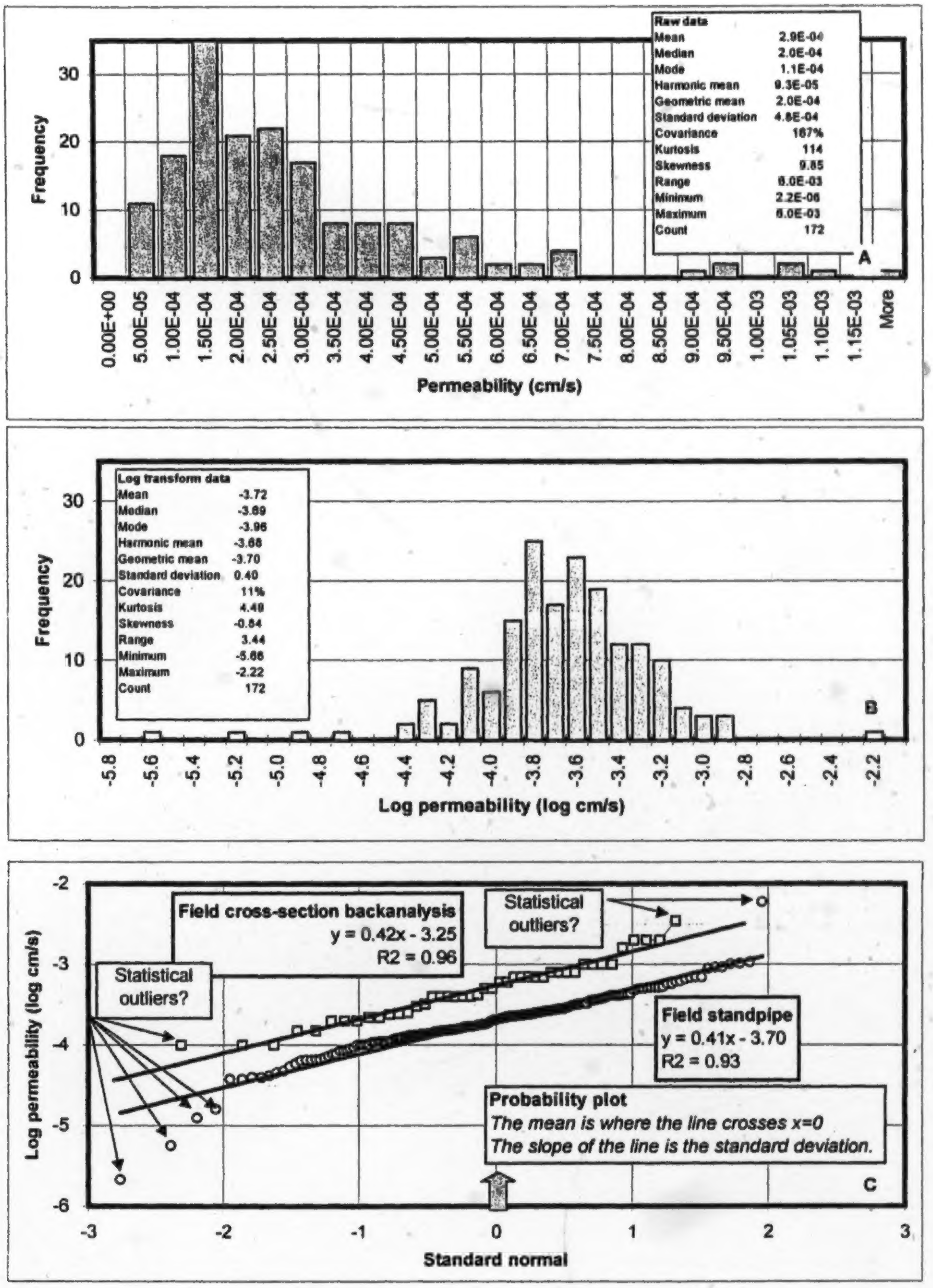


Figure 6-5 Histograms of tailings permeability data from various test methods.

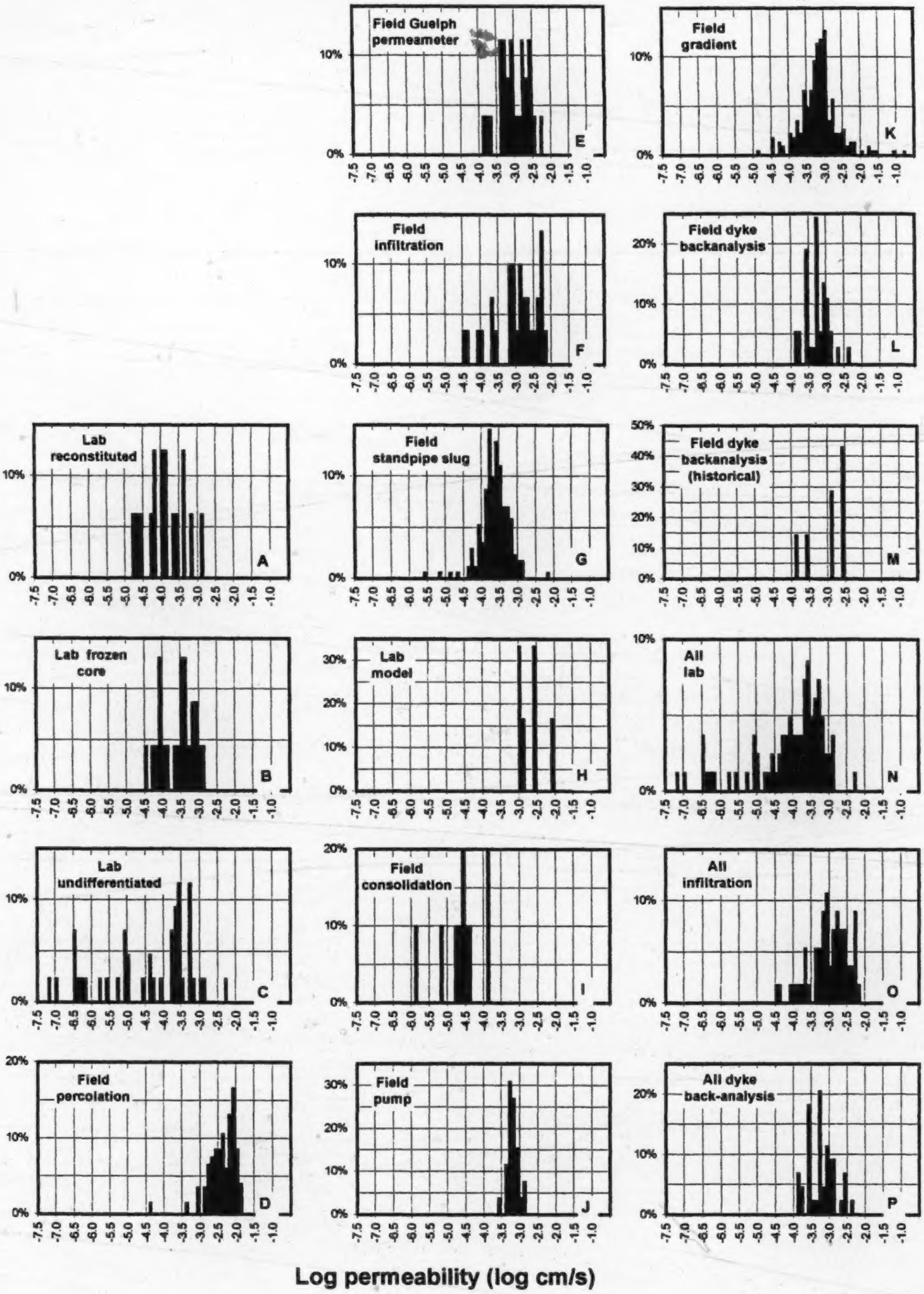


Figure 6-6 All tailings sand permeability data plotted according to volume of material tested

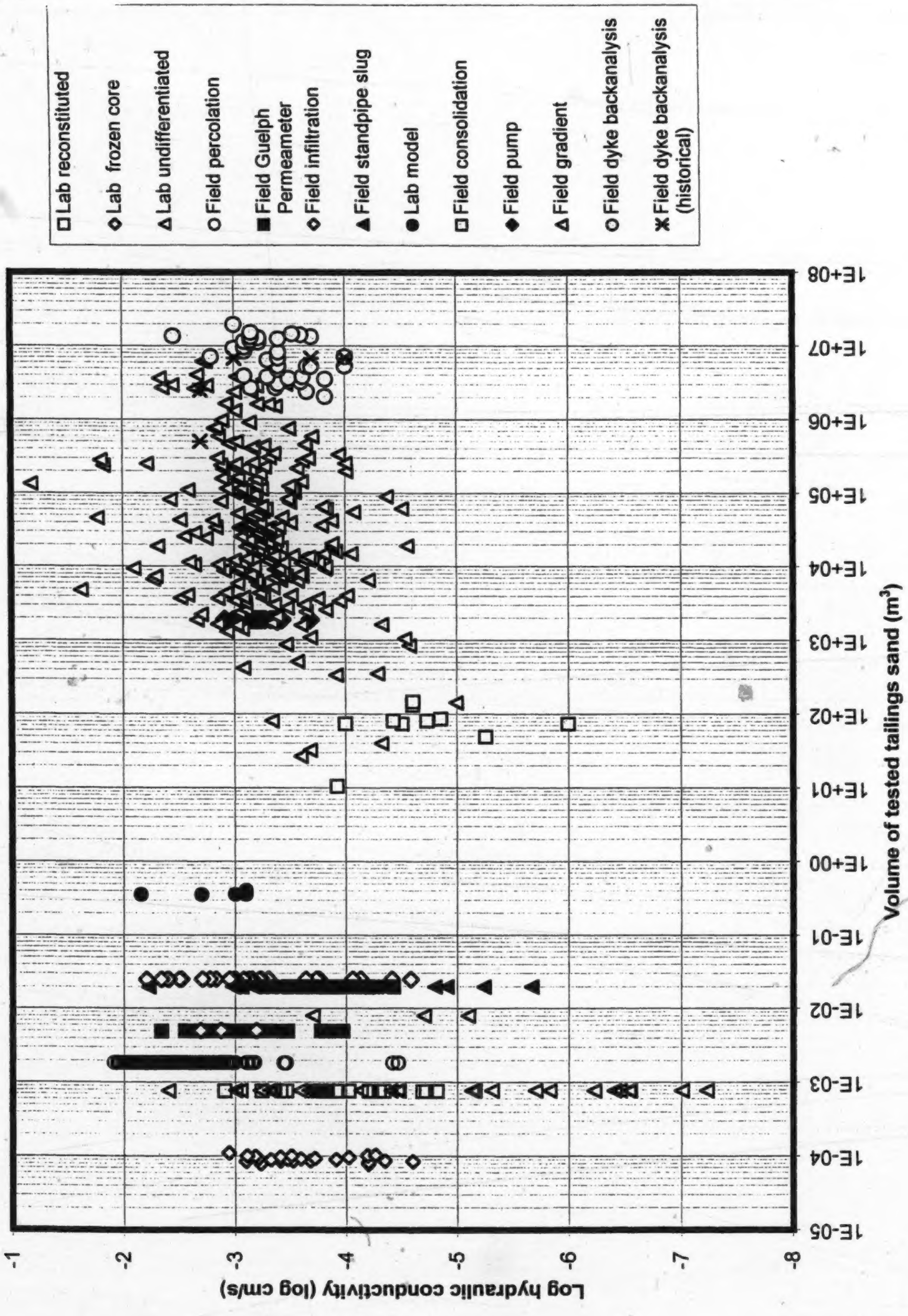


Figure 6-7 Typical cross-section for dyke seepage analysis at Syncrude's Mildred Lake Settling Basin.

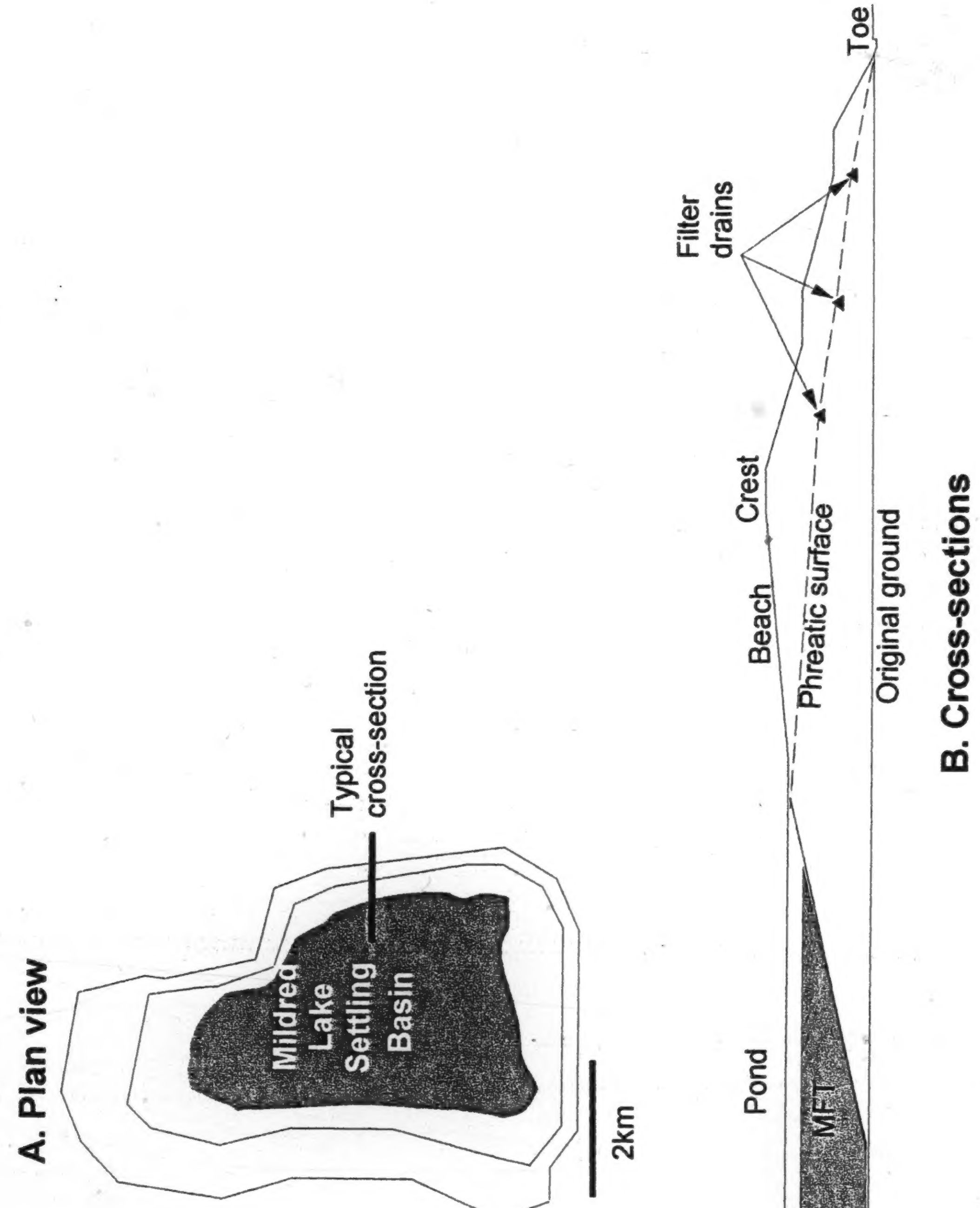

A. Plan view
Mildred Lake Settling Basin
Typical cross-section
2km
B. Cross-sections
Pond
MFT
Beach
Crest
Phreatic surface
Original ground
Filter drains
Toe

Figure 6-8 **Tailings sand data plotted classified according to non-surface (Figure 6-8A) and surface (Figure 6-8B) material. Curve fitting follows the framework of Schulze-Makuch et al. (1999).**

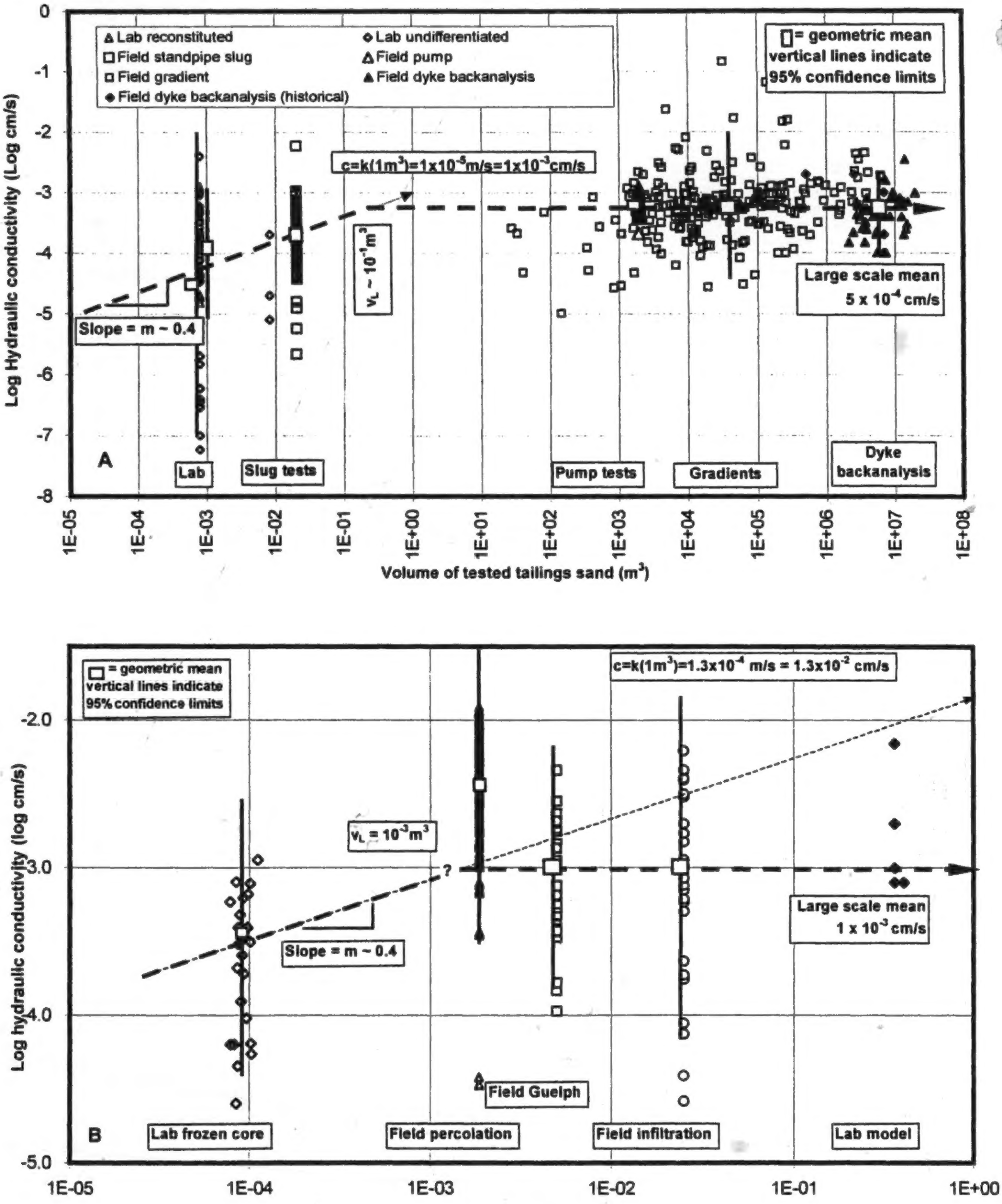


Figure 6-9 Power law averaging to attempt to upscale permeability values. Figure 6-9a uses laboratory data and achieves a partial fit for p=0.8 and p=-0.25 for horizontal and vertical permeability data respectively. Figure 6-9b indicates failure of the method to upscale from standpipe slug test data.

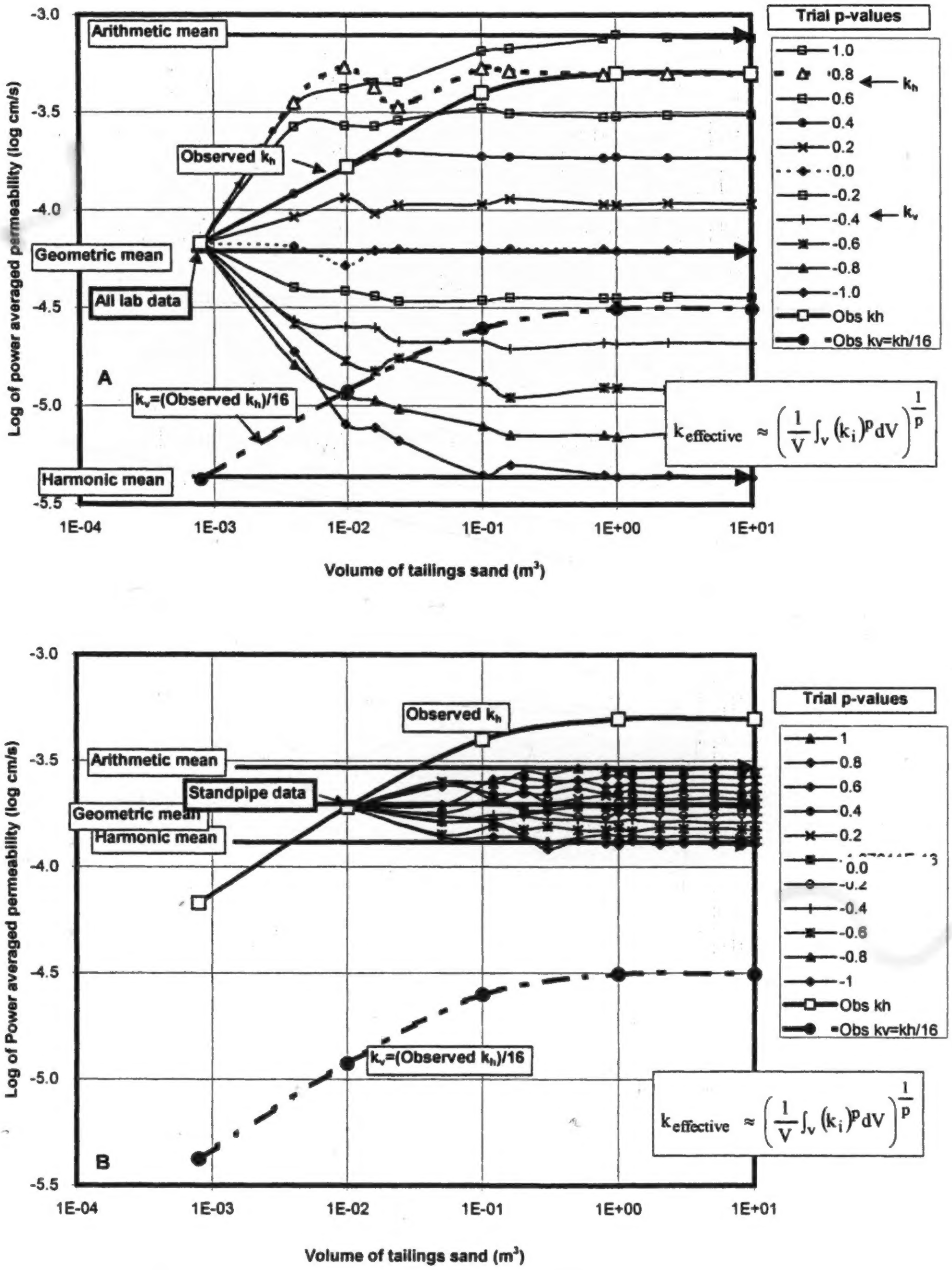


Figure 6-10 Percolation permeability test autocorrelation analysis.

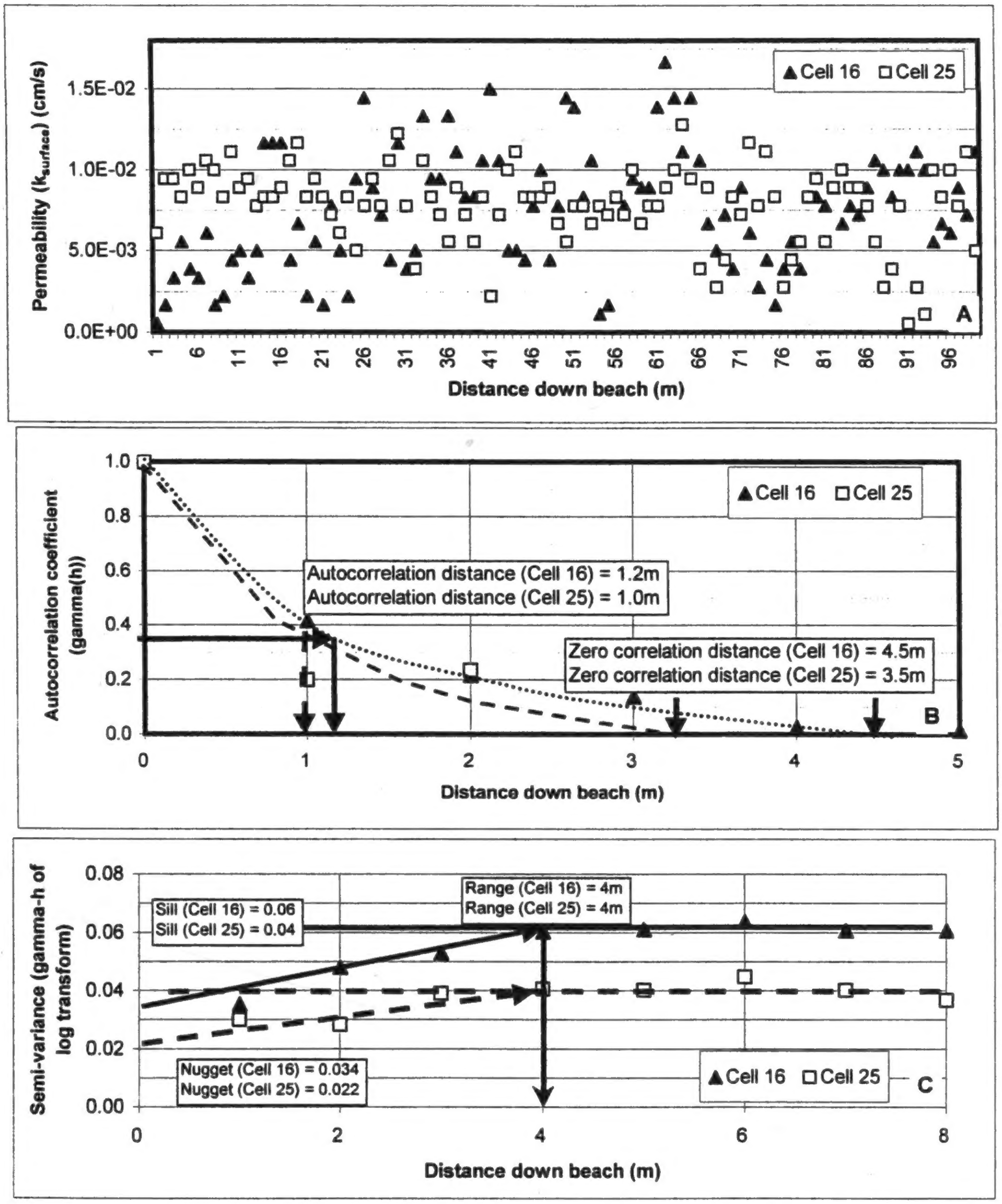


Figure 6-11 Standpipe slug test permeability autocorrelation analysis

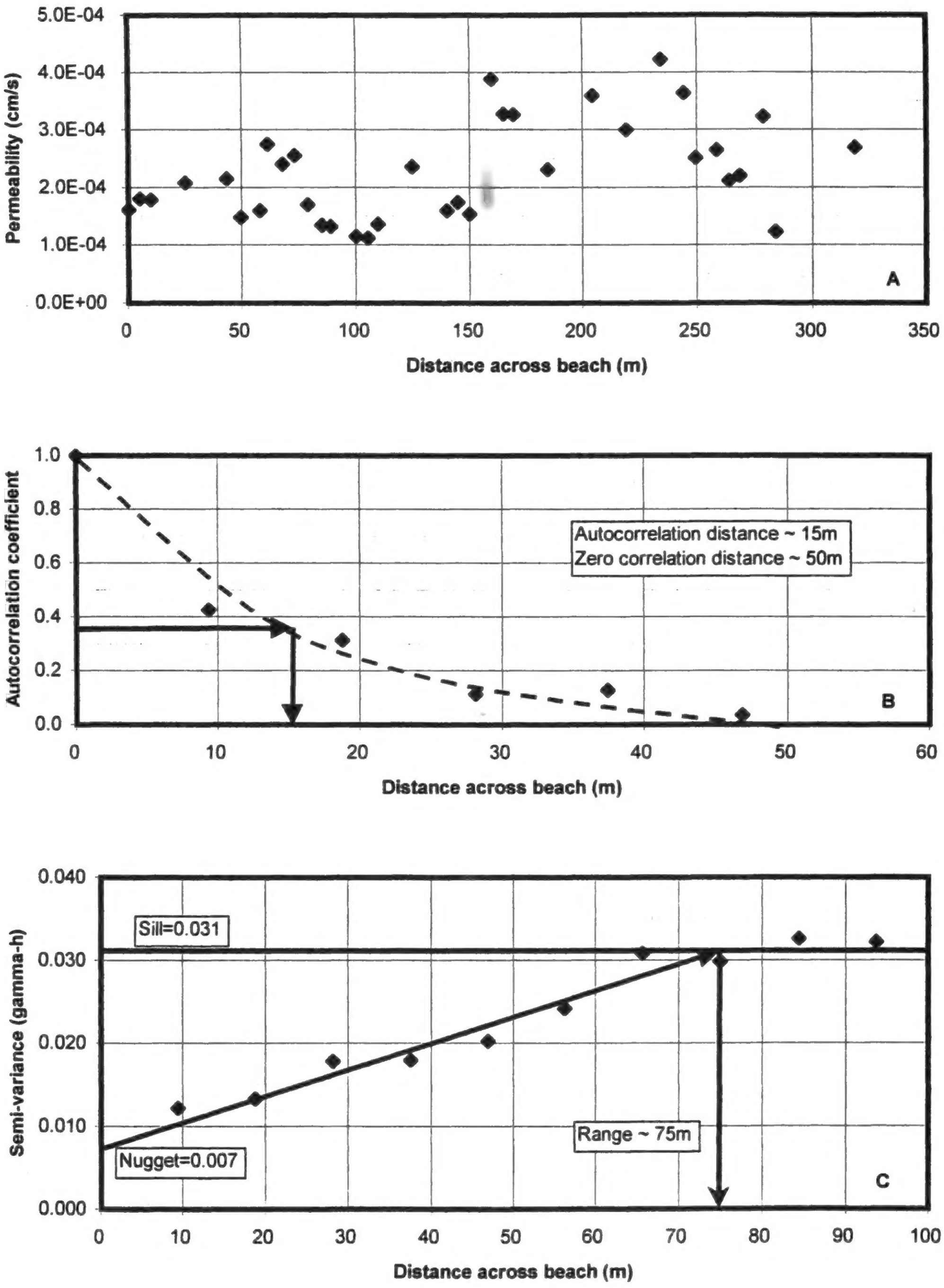


Figure 6-12 Dyke seepage back analysis permeability autocorrelation analysis

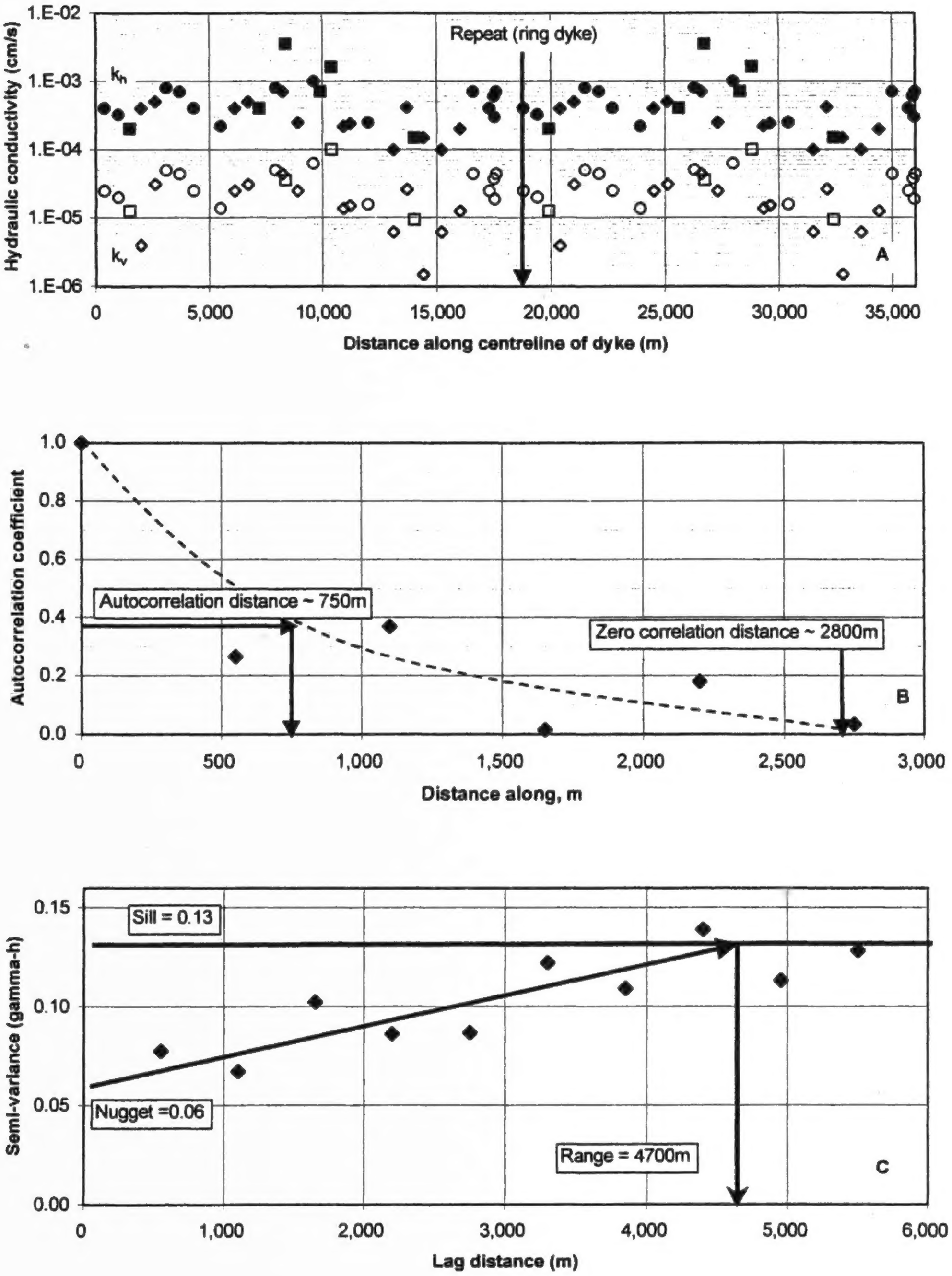


Figure 6-13 Cone tip resistance autocorrelation analysis

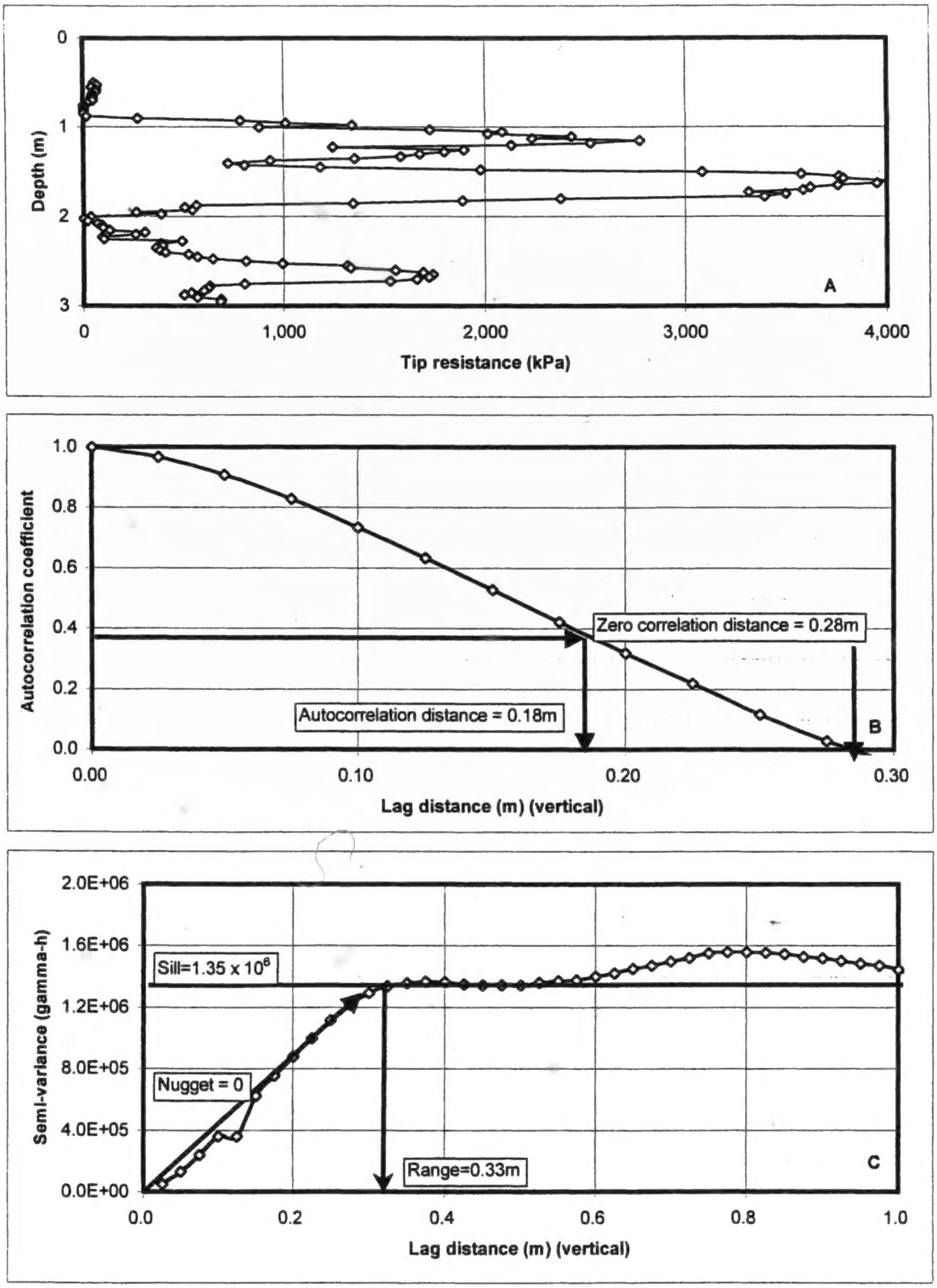


Figure 6-14 Scattergrams of cone tip resistance data residuals at various lag distances. This is an alternative presentation to the autocorrelation diagram in Figure 6-13b.

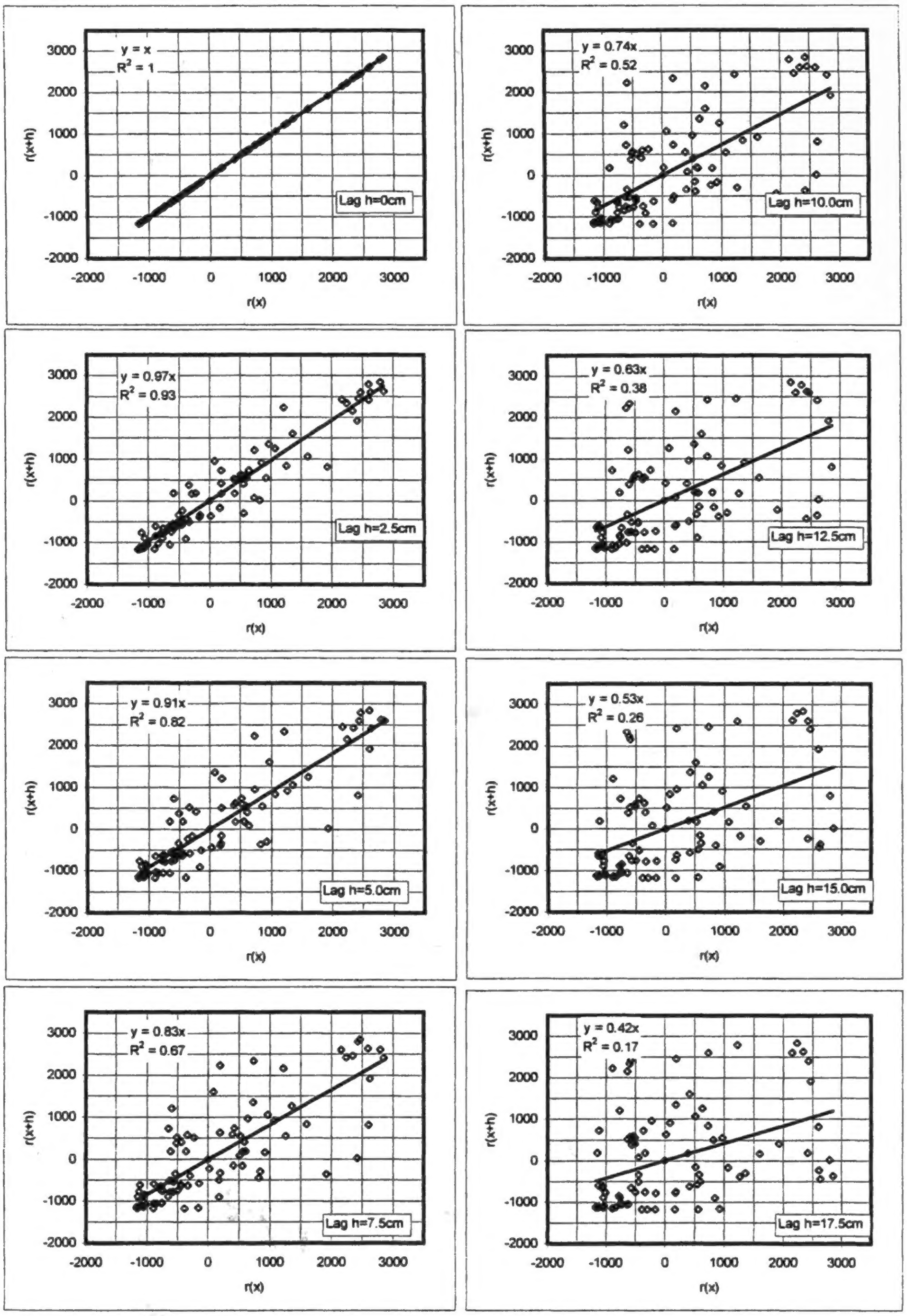
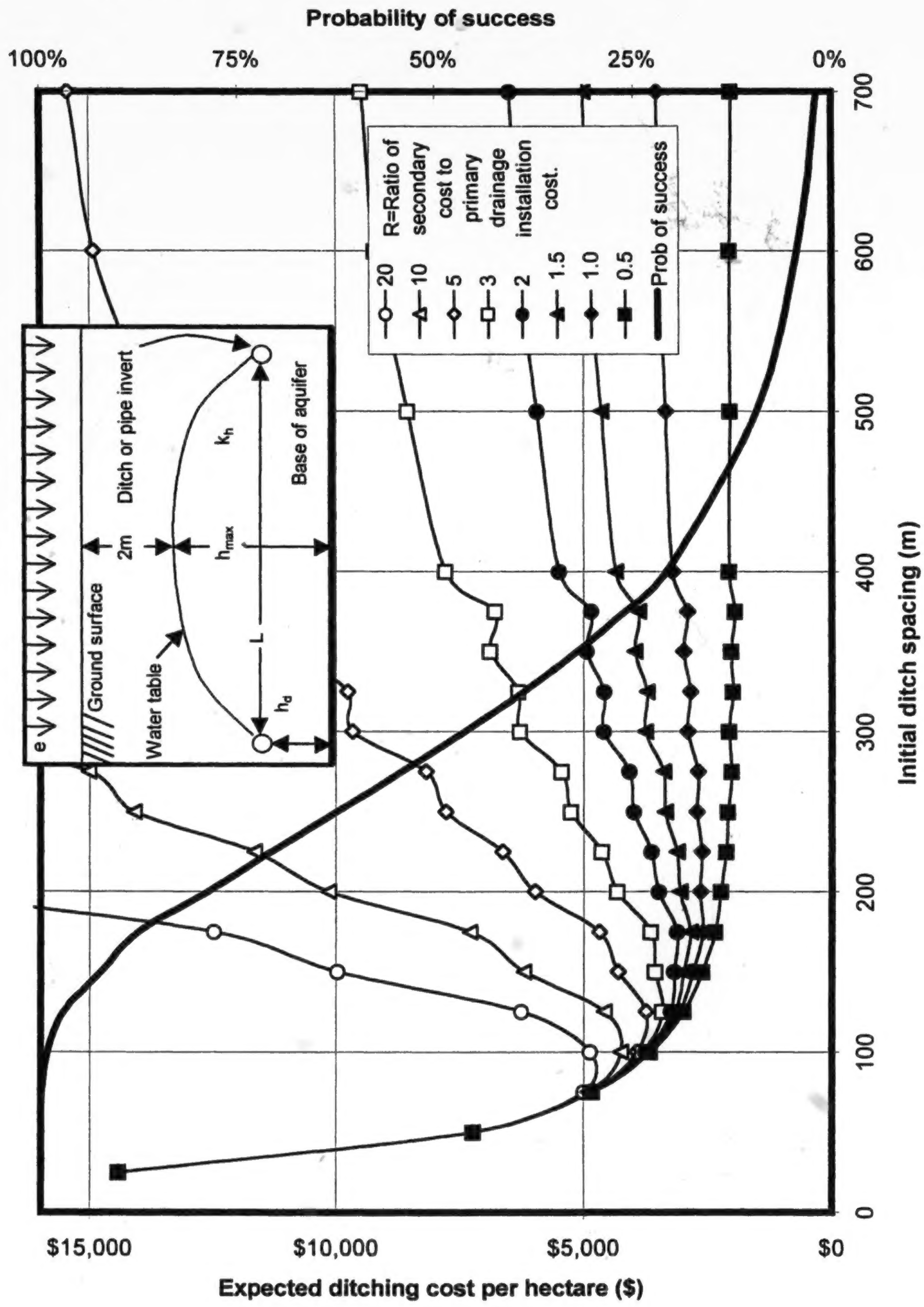


Figure 6-15 Probability of success and optimal costs of initial drain spacing for worked example



Chapter 7

Accommodating gully erosion on constructed clay-shale landforms

7.1 Introduction

Successful reclamation of mined land requires reasonable assurance that the constructed landscape will meet intended land uses, have acceptable impacts on surrounding lands, and meet other reasonable, agreed-upon landscape performance goals. A common failure is unacceptably high rate of erosion, particularly of fine-grained substrates. Methods to predict erosion rates abound, but many are inaccurate, and even when calibrated to local conditions, may only provide estimates accurate to within an order of magnitude (Trimble and Crosson, 2000). Estimating rates of gully erosion is particularly challenging. Landscape engineers need to design landforms and landscapes to achieve and accommodate acceptable rates of erosion and landform evolution and, despite the inherent uncertainties, provide useful predictions of erosion fluxes on and from constructed mining landforms and landscapes.

This chapter provides an overview of erosion rate estimation, presents a simple laboratory and field test method for predicting rates of gully erosion of a moderately dispersive clay-shale fill, and discusses landform and landscape design methods to accommodate the inevitable erosion. A central focus of the work is the sources of error and general uncertainty in prediction, and their impact on design and performance. While the study focuses on gully erosion of reclaimed landforms constructed of dispersive clay-shale fills in the oil sands region of northeastern Alberta, Canada, methods and outcomes are broadly applicable to other mine reclamation and landscape construction projects.

7.2 Background

Definitions

The literature on erosion is complicated by inconsistent terminology so for clarity, this section provides definitions of terms used in this chapter.

Sheet erosion is soil particle detachment and transport due to broad overland flow. A *rill* is a small erosional channel capable of being tilled across in agricultural areas or traversed by a pick-up truck in a mining area. Rills may occur singly or in *rill fields*. A *gully* is an erosional channel that receives intermittent (ephemeral) flow that is similar to a rill but cannot be traversed with a pick-up truck and often involves erosion of subsoil. An *active gully* is one that continues to erode (by downcutting, headcutting, or widening). An *inactive gully* is one that is largely stable, usually vegetated, and may have been created by processes no longer active.

A *tunnel* is a subsurface pipe usually caused by a combination of solution and mechanical erosion (by piping or karst forming processes). A *landslide* is the movement of a mass of rocks, earth, or debris down a slope and may trigger or be triggered by erosion by surface water. A *swale* is a shallow watercourse designed to convey ephemeral flows with minimal erosion. *Vegetated swales* are protected by upland or wetland vegetation whereas *armoured swales* are lined with rock riprap. Swales with minimal catchment are often unengineered. A *permanent stream* is a natural or constructed watercourse with continuously flowing water, often located adjacent to a constructed landform, and subject to biogeochemical water-quality goals if it is deemed a *receiving stream*. An *offsite impact* is the effect of disturbance – especially erosion, sedimentation, or water quality changes – beyond a compliance boundary. For mine sites, most erosion impacts are *on-site* or even *on-landform* – that is, redeposition occurs close to the erosion area.

Dispersive erosion is slow, typically low-energy erosion dominated by physiochemical interactions between some clay particles and eroding water and is sometimes referred to as *colloidal erosion*. *Bulk erosion*, in contrast, is the more rapid, higher-energy detachment and transport of larger particles and in particular, soil aggregates. The *critical shear stress* is the boundary shear stress that which divides dispersive and bulk erosion rates. The *erosion rate* is the mass of dry solids removed from a unit area (in plan view) per unit time as measured at the distal end of the area of interest and in this chapter, is equivalent to the *sediment delivery rate*.

Erosion of reclaimed mine land

Poor historic performance of mines, where environmental impacts were disregarded in design and operation, has created public concern and has led to adoption of prescriptive regulatory measures to reduce off-site impacts from erosion and the subsequent transport and deposition of sediments (US EPA, 2001). Ongoing impact on streams and waterbodies by sediment loading from disturbed lands (including agriculture, forestry, mining, and construction) remains a significant environmental concern in many regions (USDA, 1997).

Most jurisdictions regard erosion of constructed landforms as either unacceptable or unfortunate. Some require the use of predictive erosion models in mine permitting processes (Sawatsky, 2002). Most regulate sediment delivery to receiving streams, generally using prescriptive criteria and extensive maintenance and monitoring programs during mine operations (e.g., Alberta Environmental Protection, 1999).

Geomorphologically, erosion is natural, unavoidable, often beneficial, and is part of the rock cycle – a planetary circulatory system. However, where local erosion rates are too high, as is often the case on disturbed land, unacceptable landscape performance may occur. Such *accelerated erosion* can result in failure to achieve targeted land uses, geotechnical instability, soil loss, poor receiving-water quality, sedimentation of wetlands and drainage courses, and may necessitate costly levels of remediation and ongoing landscape maintenance. High erosion rates are especially troublesome where off-site landscape performance is affected or where eroding materials are radioactive, acid generating, or contain high levels of metals or other undesirable constituents.

Gully erosion in reclaimed areas, especially when they involve erodible substrates, cause unsightly gullies and alluvial fans that expose mine wastes to the environment, and may contribute more to overall erosion (and subsequent deposition) than other more-easily modelled mechanisms. On the positive side, gullies also contribute to landscape diversity, reduce sheet wash, and most of the eroded sediment usually remains on-landform (Trimble and Crosson, 2000). In temperate regions like the oil sands area, gully erosion is usually the most important erosion concern and one of the top landscape design and performance issues (Syncrude, 2001).

Large planar slopes, often featured in the design of landforms because they favour sheet flow over concentrated flow, are geomorphologically immature. In most cases, a drainage system will evolve with a density and morphology that is characteristic of the climate, vegetation, slope geometry and substrate and will often be typical of drainage densities of somewhat similar natural materials. Considerable erosion may occur during the maturation of the slope and the landscape.

A common strategy to attempt to slow this maturation involves protecting erodible substrates with erosion resistant covers. For example, in the oil sands region, erodible dispersive clay and tailings sand substrates are capped with 35 to 100cm thick, densely vegetated coversoils. By design, these covers are typically orders of magnitude less erodible than the substrates. But planar covers on slopes represent only an immature, unstable equilibrium. Where the cover is fully incised by a gully – inevitable in the absence of ongoing landscape maintenance – rapid erosion of the substrate will occur as the slope moves towards a new equilibrium angle and drainage density. Similar mechanics occur in natural badlands area and other areas underlain by dispersive subsoils (Torri et al., 1994; Carey et al., 2001).

Erosion prediction methods

There are dozens of erosion prediction models. Most have been developed for agricultural areas and are design to compare predicted annual rates of soil loss from broad areas under various cropland and rangeland management techniques. Some are purely statistical models, others mechanistic. Two of the more widely used methods in North America are the Revised Universal Soil Loss Equation (RUSLE) (USDA Agricultural Research Service, 1997) and Water Erosion Prediction Project erosion model (WEPP) (Flanagan and Nearing, 1995). Much of the research on erosion rates is directed towards supporting or fitting these competing models. In particular much of the mineland erosion literature is solely focussed on fitting or improving RUSLE parameters. Aside from a few new deterministic gully erosion models (e.g., Sidorchuk, 1999; Woodward, 1999; Kirkby and Bull, 2000), these models do not consider gully erosion – mostly due to difficulties in modelling, and partly because gullies are often repaired in agricultural, forestry, or mining environments.

Because there is a wide discrepancy between predicted and observed erosion rates, models are better as research tools than as public policy and regulatory instruments (Trimble and Crosson, 2000) or for prescriptive design measures for constructed landforms. But some models may provide useful guidance for the design engineer if adequately calibrated and verified for local conditions and if the design accounts for the uncertainty.

Most erosion modelling is applied to existing sites of known topography and material properties to guide land management activities. Designers of constructed landforms, however, have considerable control over the topography, cover soil placement, initial revegetation, and to a lesser extent the substrate properties – flexibility that is generally uneconomical for farmers and ranchers and most users of erosion models. On the other hand, miners have little input into post closure land use practices and management.

Methods to estimate erosion rates include:

- purely statistical models
- subjectively determined erosion rates using expert judgement combined with a database of erosion rates of natural and reclaimed sites (natural and industrial analogs)
- surveying of existing erosional or depositional features of known age (or as determined by dating of deposits) to determine average erosion rates. Analysis of historical aerial photographs is often employed.
- site-specific empirical models that relate slope, watershed size, and rainfall
- empirical and semi-empirical or deterministic models based on laboratory and field flume measurements of erosion under simulated rainfall or flow conditions
- physically based gully erosion models
- landform and landscape scale models, often GIS based, that apply erosion mechanics or statistical relationships to predict changes in topography and erosion rates
- sediment-budget models based on watershed monitoring

Erosion and landform design

Today in Canada, few mining landforms are explicitly designed to resist erosion (see Chapters 2 and 3). In situations where declared design goals includes minimizing erosion, design and construction efforts usually focuses on designing for sheetflow – avoiding concentrating water on reclaimed slopes and keeping slope lengths below a threshold where velocities or tractive shear stresses during a specified (often a 1 in 100 year) runoff event causes rapid erosion at the toe of the slope. Long slopes are usually divided into a series of large planar segments separated by narrow level berms based on mandated prescriptive parameters or nomographs. The original design function of these intermediate berms (to safely convey water laterally to designed downswales (e.g., United States Department of the Interior, 1967)) has generally been lost and there is an ongoing debate as to whether to have them tip in, out, or be level. There is a similar debate surrounding whether or not to build dump plateaus above the slopes in with a crowned, dished, or flat topography. Like terraces, most dump plateaus are built horizontal.

The result of the current state of practice is that erosion due to overland flow on reclaimed minesites remains one of the greatest landscape performance concerns. Slopes of erodible material (especially tailings sand) show considerable gullying, loss of coversoils and vegetation, and deposition onto undisturbed areas and into ditches and creeks. Many slopes perform well only before being tested by a moderate sized (say 1 in 10 year) runoff event. Perhaps the greatest problems is the misapplication of sheetflow strategy – it should be applied only to small areas and short slopes. When it is applied to large areas, the probability of concentrated flow becomes high and unwanted gullying results. Flow may be concentrated by minor irregularities on slopes and berms, seepage induced gullies, disturbance due to vehicles, change or loss of vegetative cover, leakage of irrigation systems, and in rills and gullies caused by exceedence of design runoff events. Concentration of flow by diagonal access ramps often occurs on tailings slopes. Overtopping of shallow pools on berms and flat plateaus is particularly common and leads to large gullies. In short, application of sheetflow to design of large areas does not generally produce acceptable landscape performance where erodible covers or substrates are involved.

The design and construction of landforms and landscapes goes beyond designing to control surface erosion and also includes other elements of surface-water hydrology, geotechnical, groundwater, soils, vegetation, and wildlife as part of overall mine planning, scheduling, and economics. Whereas the overall bulk of the landform is largely governed by mine planning and geotechnical constraints, the overall shape of the surface of the landform is largely governed by erosion control. In other words, the overall physical stability of a landform is usually the primary design consideration. In most cases, constraints from other specialists are iterative modifications to the basic mine planning, geotechnical, and surface-water hydrology design.

New design measures being tested at Syncrude and elsewhere attempt to mimic natural conditions to build landforms with more mature topographies – a technology referred to as landform grading (Schor and Gray, 1995). Landforms are constructed with small, well-defined watersheds that concentrate flow into swales and channels. Simple nomographs are created to design the swales and channels based on a combination of natural analogs (Keys et al., 1995) and local hydrologic conditions and material properties. If the catchment areas and slope angles exceed certain (conservative) thresholds, watercourses are engineered as vegetated swales or rock armoured channels. Done in a timely manner, landform grading costs are indistinguishable from traditional regrading costs and are a minuscule incremental cost per cubic metre of fill placed.

To make a more robust and resilient landscape, and to address residual risks and uncertainties, secondary lines of defence such as self-armouring with bouldery ground or buried rock berms are added to critical or erosion prone areas. Downstream areas are designed to accommodate deposition by oversizing constructed wetlands, ensuring constructed channels are deeply incised, and by offsetting watercourses from the toes of slopes. In sizing these features, some prediction of future erosion rates is required, especially when justifying offsets that increase the area of disturbance or affect the final volume of the landform.

7.3 Study area and materials

Study location

The Syncrude Canada Ltd Mildred Lake Operation in northeastern Alberta, Canada, is one of the largest mines in the world (Figure 7-1). It mines 450,000t (220,000 m^3) of oil sands ore each day. Overburden stripping generates about 120,000 m^3/day (40 million m^3/year) of Clearwater Formation clay-shale (Kc) fill. This overburden is mined with shovels and trucks, and used to build large out-of-pit overburden storage areas (known operationally as dumps) – creating 40-m high constructed hills above the otherwise relatively flat landscape. At closure, Kc fills will form the substrate of about 40 percent of the reclaimed landscape – about 80 square kilometres (Syncrude, 2001) About half of the oil sands mines in the region will have similar Kc landforms.

The oil sands region is located in the mixed-wood ecoregion of Canada's boreal forest. The climate is continental with long, cold winters and short warm summers. Annual precipitation is about 450 mm, with half falling as snow. Much of the rainfall occurs during short intense thundershowers in summer months. Runoff is generally greatest during spring snowmelt when much of the ground is frozen – hydrology designs are often governed by late-spring rain on snow events. Average humidity is 80 percent and average annual potential evaporation is 550 mm.

The main mandated land use goal of mine reclamation in the oil sands region is to return the land to productive forest uses with emphasis on re-establishing land capability for commercial forestry, wildlife habitat, and traditional land use (Syncrude, 2001). Regulators mandate return of land to a maintenance-free condition (Oil Sands Vegetation Reclamation Committee, 1998) and have expressed concern about the risk of gully erosion on reclaimed land (Hale, 2001).

Erosion rate testing was performed at Syncrude's Mildred Lake Operation. Observations, sampling for the laboratory programs, and field testing were carried out at an overburden storage area, know operationally as the SW 30 Dump (Figure 7-2). This 90m-high, 85-hectare hill constructed of 100 million cubic metres of predominantly Kc fill is described in greater detail below.

Material properties of Kc fill

Overviews of the geology of the Athabasca Oil Sands region are provided by Carrigy (1973) and Mossop (1980). The variability of the Kc fill is described in detail because it affects the variability of erosion rate predictions.

The Kc fill at the SW30 dump is a mixture of Early-Cretaceous Clearwater Formation sandy clay (Kca and Kcb), Clearwater-Wabisca Formation clayey glauconitic sand (Kcw), low-grade McMurray Formation oil sand (Km), and Pleistocene glaciolacustrine clays (Pl) and clayey glacial till (Pg). Below 320m elevation, the dump contains higher proportions of sandier fill (less Kca and Kcw). Material placed above the 320m is generally clayier (it is mostly Kca and Kcw) and is dominated by clay-shale material (a class of material composed of high-plasticity fissile argillaceous shale that weathers rapidly to clay). Table 7-1 and Figure 7-3 provide a summary of the index properties of materials sampled from the dump surface just prior to soil capping. Each of the main index properties has a normal distribution of values reflecting the variability and mixing of the materials during placement. Most of the material is at its natural moisture content which is typically well dry of Proctor optimum moisture content.

Table 7-2 summarizes geotechnical, geochemical, and mineralogical data for the material tested in the erosion flumes. Figure 7-4 plots the material on soil dispersivity chart (Sherard et al., 1976) which is intended to identify susceptibility of catastrophic tunnel erosion (piping) of clays used in embankment construction. The Kc fills generally plot in the transition zone (Zone C) whereas Pl plots in the nondispersive zone (Zone B). The Kc fills are likely lumpy mixtures of materials that are in Zones A and C with Pl materials from Zone B.

Spatially, the material properties are extremely variable, with individual lumps varying in mass from 1 kg to 100 tonnes. The dump is built in 5-m lifts, and while materials vary with each truckload, there are distinct lateral and vertical trends within these lifts. In particular, alternate lifts are wetter or drier reflecting a strategy of keeping half the dump trafficable in wet weather. The top of each lift also tends to be very dense (due to overcompaction from the haul truck tires) and loose to dense below. The dump is moderately jointed due to gaps between lumps, cracks caused by traffic, regrading activities, subsidence, and lateral spreading movements during construction. Preliminary results from a groundwater investigation within the dump suggest a discontinuous water table of highly saline water.

The dump also contains cobbles and boulders, known locally as siltstones, from indurated (cemented) zones within the Clearwater and McMurray Formations. Volumetrically, they typically represent 1 to 5 percent of the dump, generally mixed randomly (but not uniformly) within the fill. Upon exposure, some siltstone clasts weather quickly – disintegrating to pebble or sand size within months while others are more durable. The clasts collect in the base of gullies – in some cases accelerating erosion, other times helping to armour the channels, depending upon the relative amount, size, and durability of the clasts. The fill has a very small percentage of intermediate size particles between the sandy clay and the boulders that could help to act as a transition or filter material. Natural creeks in the region are armoured by briefcase-sized siltstones.

Construction and reclamation

The fill and the placement methods are ever changing depending upon availability of source materials, design and operational strategies, and weather at the time of placement. After the completion of each lift, the next lift is set back from the crest to allow for a final benched landform. The repose angle of intermediate slopes between lifts is 1H:1V. Cracking and sloughing of these faces is common and occasionally leads to tunnel erosion caused by shallow ponded water entering cracks that form up to 25 m away from the crest.

After construction, dozers push down the slopes to 5H:1V or flatter, obliterating benches in the top 30m of the dump. This area is a large field trial for landform grading and most slopes were sculpted into a series of shallow swales and ridges. The top plateau of the dump was dished so water would not pool and run over the crest – it drains along a vegetated watercourse constructed along the main haul ramp. The crest areas are designed as Hortonian regions of no erosion (at least by overland flow (see Horton, 1945)). Non-uniform long term subsidence of the dump is expected to reach several metres which is partially factored into surface-water hydrology designs.

After regrading, the area is required to be capped with 20 cm of peat overlying 30 cm of secondary material over 50 cm non-sodic soil (Alberta Environment, 2001). This prescriptive reclamation cap is designed to provide suitable growth medium for productive forest. The area is revegetated with a barley nursecrop and later planted to forest species – mostly white spruce and aspen and a shrub understory. Invasion of native plants dramatically affects the composition and density of the understory species as well as the hydrologic properties of the cover, especially infiltration and percolation. Planting schemes are designed for eventual logging.

Field erosion trials discussed below occurred on a bare, planar, 60m long, regraded, 10H:1V slope at 325m elevation after regrading but prior to cover soil placement. Substrate materials are described in Table 7-2.

Table 7-3 describes the initial water chemistry of the eroding waters used in the flume experiments. For surface erosion, typical water chemistries will be similar to tap water (TW), natural runoff water (WID), and Kc surface runoff water (PP). For comparison, tailings recycle water (RCW) and composite tailings runoff water (CT) were used (if subsurface erosion in compacted Kc dykes were to occur, this would be the water). As described later, the chemistry, and particularly the ionic strength of eroding waters, changes while it is in contact with the eroding materials, particularly Kc.

7.4 General observation of field erosion performance

Natural slopes

There are many inactive (remnant) and few active gullies in natural Clearwater Formation bedrock exposures. The most active gullies occur on erosion slopes on retrogressing 60-m high river valley walls. They have stepped terraces and are overall slope gradients of 7 to 13 percent. They are well armoured by tabular siltstone boulders (creating numerous 1-m to 3-m high falls), coarse woody debris, and are incised about 10m into the slope. A colluvial fan of siltstones is present at the base of the gully. Together, the active and stable gullies have a spacing of 200 to 300 m and a drainage density of about 3 to 5 km/km^2 forming "scalloped" topography that dominates river valleys in the region.

Gullies on the SW 30 dump

Existing gullies on the unreclaimed areas of the dump were generally caused by water that had ponded on flat benches that had overtopped and flooded down slopes, typically during thunderstorms. The resulting gullies are typically 0.3 to 1.0m deep, 0.1 to 0.3-m wide (at the base), with 45 to 70° side slopes and slope gradients of 5 to 20 percent. Some gullies are linear, while others are highly sinuous. Infrequent soil bridges at the ground surface and the numerous in-gully tunnels around obstructions indicate that tunnel erosion (piping) is a contributing erosion mechanism. The base of the gullies generally shows a distinctive "step and stair" erosional pattern – an inherent rhythmic series of small ledges and plunge pools and modified by irregularities and layering within fill. Typically, rock that collects at the base of the gullies does not provide significant armouring – erosion of the clay is often accelerated around the periphery of the sporadic boulders. Most gullies are unvegetated – the exposed saline / sodic clay-shale provides a poor growth medium for most plants (their electrical conductivities and sodium adsorption ratios are higher than most plants will tolerate).

Where Kc is exposed on the dump, it usually dries rapidly, forming first a fissured surface marked by small polygonal "alligator" cracks, then a dry powdery surface several centimeters deep after several months. Within gullies, conditions are usually more moist, but surface dessication is also common. Infiltration into the Kc also varies – some areas sealing due to the expansive clays, other areas develop secondary porosity due to cracking and tunnel erosion. Freeze-thaw and geochemical reactions are also important to the Kc physical and geochemical properties.

Several large gullies left over from construction were present near the base of the dump. These gullies were about 50m long and averaged about 5m deep, likely the result of ponded water flowing over the crest. The walls of these large gullies were moderately stable, with slopes of about 1H:1V and a base width of 20 to 80cm. Unlike most gullies which initiate near the toes of slopes, most gullies on the 30 dump are continuous from crest to toe and are initiated by overtopping of ponded water on the top of the dump.

Drought conditioned prevailed during much of the study period – there was little new erosion during the observation period. Recently regraded portions of the study area only showed minor rill fields in a few short steep areas. Rill cross-sections were typically rectangular, 2 to 4cm deep and 5cm wide, deeper and narrower where the material is looser, extended from crest to toe and spaced about 30cm apart. Deposition occurred in small, soft, shallow sloping alluvial fans at the base of the slopes. The patterns of rill field erosion are often dominated by dozer track patterns from final regrading.

Gullies on similar constructed landforms

On other reclaimed overburden landforms, gullies that have incised through the cover are usually caused by overtopping of shallow pools of water in upslope unreclaimed areas during construction. Gullies are slightly sinuous, 1 to 1.5m deep, and are naturally revegetating when the gullies become less active, partially because the base of the gullies is usually moist and contain bank slough from the coversoil. Active gullies and larger inactive ones are repaired, smaller ones left. In contrast, gullies on tailings sand slopes tend to be deeper, wider, and can cause considerable damage to the reclaimed landscape.

7.5 Erosion flume tests

The following sections describe a series of 99 laboratory and field flume tests. Test methods, observations, analytical calculations, and results are presented. The database of the erosion flume trial data is presented in Appendix E. The goal of the testing program was to develop parameters for prediction of gully erosion rates on reclaimed Kc landforms, and to provide an estimate of uncertainty in results and predictions related to rates of erosion.

The tests focused on Kc fill from the SW 30 dump and also included some higher plasticity Kca and lower plasticity Pl fills, also components of the dump, for comparison. Tailings sand, a highly erodible, uniform cohesionless very fine sand, was also tested for comparison. Most of the eroding water used was natural runoff water from the SW 30 dump (PP), lease drainage ditches (WID), and tap water originally from the Athabasca River (TW) that have moderately low TDS, similar to that which would be eroding the SW 30 Dump, and available in unlimited supply. For comparison, distilled water (DW), and two tailings waters (CT, RW) were tested. One suite of tests also used heavily limed tap water. These waters had to be recirculated over the flumes hundreds of times over the course of each trial.

7.6 Laboratory flumes

Procedures

The 2.66-m long wooden laboratory erosion flumes are shown in Figure 7-5. Dimensions were chosen to test typical rill and gully geometries, and to be long enough to measure average erosion over a series of "step and stair" patterns observed in the field and seen to form in trial laboratory flumes. The flumes proved too narrow to allow sinuosity to develop.

Preparation

Several tonnes of Kc and other soils were transported with a front-end loader to the floor of a large warehouse and to an outdoor field test site and tarped. Lumps were broken up or removed and all test material passed through a 1.5cm screen and homogenized. A specific amount of soil (for example 29kg for Kc) was measured out and compacted in two lifts using an electric jackhammer with a specially welded foot to attempt to mimic field densities. All material was compacted into the flume at its natural water content (typically 20 percent) to a uniform thickness of 3cm (the height of the wooden weirs at each end). Achieving consistent compacted densities remained a problem throughout the program. Sample retains were kept for moisture and grain size. Flumes were marked at five stations (at 30cm, 100cm, 150cm, 200cm, and 260cm) for flow depth and width measurements. The flume was then inclined to the desired slope gradient, S.

For each different soil-water couple, six flume trials were run simultaneously to span average shear stresses from 1 to 20 Pa by using a combination of water discharges from 1 to 20 litres per minute and slope gradients, S, of 1 to 20 percent. Average flow velocities ranged from 3 to 100 cm/s.

For non-recirculating flumes, a 2-inch (50mm) pump was used to transfer water from a nearby ditch into a shallow tank, from which small pumps with garden hoses distributed water to each flume. Before the test, a water sample was taken, the temperature and conductivity recorded, the clay fill material sampled and the compacted surface of the clay described. A set of six flume tests required about 20,000 litres of water, 200kg of soil, and four people working a 10-hour day.

For tests where the water was recirculated, an 80L garbage can was used as a reservoir for each flume. Fifty litres of water were recirculated by a small pump suspended 20cm from the base of the reservoir. Some water loss was common, which complicated analysis. (It was found that recirculating the eroding water is best avoided for a variety of reasons described below).

Testing

At regular times during the test (at 2, 10, 30, 60, 120, 180, and 300 minutes), a 1-litre jar was filled with the discharge water (including suspended and bedload sediment) from a chute at the end of the flume to measure flow rate (Q) and solids content (a measure of the instantaneous erosion rate). At each of the five station locations (30, 100, 150, 200, and 260cm), the flow depth (d) and width (w) was measured using a small ruler.

End of test

At the end of 300 minutes, or when more than 10 percent of the length of the flume had worn down to the wooden base, a final water sample was taken and the pump shut off. The surface was photographed and described and samples of the surface wet zone, the middle moist zone, and the lower drier zone were sampled for moisture content.

There was so much swelling of the soils in the flumes (sometimes up to 200 percent of original height) that volumetric measurements of the remaining flume material, a common technique for measuring sediment loss, proved useless. Erosion rates were therefore determined by measuring the sediment concentration in runoff water.

Calculations

For each trial, at each of 5 measurement stations, and at each at of 6 readings, flow parameters (flow area (A_f), depth (d), width (w), average flow velocity (v), shear stress (τ), and Manning's roughness coefficient (n)) were calculated. Representative values of each were chosen for the entire flume. This averaging of measurements taken at fixed spacing and times ignores the spectrum of velocities and shear stresses and in particular some of the higher localized shear stresses that dominate erosion rates, but done in a consistent manner provide a self-consistent measurement system, and is perhaps a benefit of the model when applied to field conditions. The importance and effect of this averaging is discussed later.

The average flow velocity at each station (for each reading time) was calculated by:

$$v = \frac{Q}{A_f} \qquad \text{Eq. 7-1}$$

The shear stress, at each station was estimated by:

$$\tau = \gamma_w RS = \frac{\gamma_w wdS}{2d + w} \qquad \text{Eq. 7-2}$$

where R is the hydraulic radius of the wetted channel and γ_w in the unit weight of water (Chow, 1959). The erosion rate, ε was calculated for each interval from the amount of dry solids eroded per unit time per unit area (in plan view) under active erosion.

Each measured erosion rate (g/m^2/h) was plotted against time (h) and average shear stress (Pa) and fit with a multiple linear regression using either of these equations:

$$\log \varepsilon = A \log \tau + B \log t + C \qquad \text{Eq. 7-3a}$$

$$\varepsilon = \tau^A t^B 10^C \qquad \text{Eq. 7-3b}$$

For the recirculating tests, it proved impossible to estimate the interval erosion rates because of discharge sampling errors (the bedload component had a large variance) and redispersion of some of the bedload sediment in the garbage can. Results were also complicated by the fact that the water chemistry, sediment carrying capacity of the eroding water, and water temperature continued to change throughout the test. Overall erosion rates of these recirculating tests were estimated by summing the suspended load and dry solids in the base of the garbage can at the end of the test and averaged over the whole length of the test.

Manning's roughness coefficient (n) is important to estimating flow depth for a given discharge, slope, and flow width and is discussed in greater detail below. It was estimated from Manning's equation by back analyzing average flow conditions during the flume tests:

$$n = \frac{A_f}{Q} R^{\frac{2}{3}} S^{\frac{1}{2}} \qquad \text{Eq. 7-4}$$

where R is the hydraulic radius of the wetted channel (Chow, 1959).

For the half-dozen instances where a single data value was missing from the test (due to missing or spoiled sample or datapoint) the datapoint was interpolated based on adjacent datapoints (Rock, 1988).

Results

Visual observations

The Kc clay swells rapidly and greatly with all water chemistries, becoming an extremely soft gel at the eroding surface. At very low velocities, the erosion process is dominated by dispersion, but at velocities above about 2 cm/s, the process is dominated by detachment of flakes and granules.

For the flumes with very low slope gradients, water pooled over the entire 20cm width of the flume to a depth of 1.0 to 1.2 cm with velocities of 3 to 8 cm/s. In-channel deposition, particularly near the distal end was common. When the flumes were steeper, downcutting was common. Flow widths of 10 to 15 cm were common, with flow depths of 0.5 to 0.8 cm and velocities of 40 to 100 cm/s.

The surface of the compacted Kc was initially moist, smooth, compact, with slightly drier planar flakes 0.5-mm thick, 5-mm diameter that had a distinct, "sharp" angular appearance. Upon wetting in standing water for a few minutes, the clay flakes swell greatly, becoming ellipsoidal – the length remains at 5 mm, but swells to 3 mm vertically. This swelling increases the particle's volume (end hence its drag coefficient) while reducing its density. When the eroding water starts to flow at a velocity of more than about 2 cm/s, the clay gel that forms the outer covering of these particles is quickly stripped away, sometimes when the particle is stationary or sometimes while it is rolling as bedload. As the particle reduces in mass and size, it eventually starts to erode and move (or increase in velocity if already in motion). In-place particles swell quickly and take on a dull, subrounded appearance. If the velocity is high enough, this gel material is eroded as it forms.

The particle may be jacked up into the flow by the swelling, causing local eddies and micro-erosion before it is carried away. When average velocities are slow, different areas of the flume show different mechanisms depending upon the local flow conditions. When velocities are high, particle (bulk) erosion, mostly as bedload, dominates.

During transport, the ratio of suspended to bed load averages 50 percent but varies from near 0 to 100 percent. Most of the suspended load is generally carried out of the flume, but some reflocculates and settles in low flow velocity areas. Bedload generally rolls along the base of the flume and may be carried out of the flume or be redeposited. Many of the particles settle into a fan at the base of the deposit, commonly as 1-mm diameter grains. These are particularly soft and susceptible to dispersion and re-erosion. In higher ionic strength waters, the particles remain less dispersed and more likely to be redeposited in the flume. Erosion rates reported in this study are the total erosion rates (suspended + bedload).

Over a couple of hours, the wetting depth of the parent material goes to about 5 mm (soft) and moist (to another 10mm). The wetting depth is greater near the discharge. The Kc, initially at 20 percent moisture content (mass of water over mass of solids), swells to 40 to 60 percent moisture in the top 5mm. A middle moist layer is typically 40 to 60 percent moisture. The material in the bottom 1cm swells to 30 to 40 percent moisture. If flow velocities are high, the upper most swelled layer is thin due to its rapid erosion.

At high enough velocities, a subaerial channel will cut down into a rectangular. It quickly forms the step and stair pattern of plunge pools and falls (see Jones, 1987; Bennett, 1999). Little sinuosity was observed. Erosion is augmented by plucking of 5 to 10-mm diameter lumps through headcutting of each step.

A fourth type of erosion was also seen – liquefied flows resulted when water was discharged over tailings sand and loosely packed Kc in some flumes at 10 and 20 percent slopes. Much of the movement was triggered by interfacial sliding along the wooden sides and base during the first minutes. Similar small mudflows are seen on the SW 30 dump, where loose or colluvial clay-shale becomes wet and starts to creep downslope.

Little tunnel erosion was seen in the laboratory flumes, likely because the natural soil structure was obliterated by screening and compaction.

For one suite of tests, 3000 ppm of quicklime (hydrated calcium carbonate) was added to tap water to arrest dispersive erosion. This brought the initial pH of the eroding water to 12.3 with an electrical conductivity to 3.2 dS/m and a calcium content to about 800 ppm. The Kc became saturated and very soft to full depth, swelling to twice its original thickness. At low shear stresses, there was no dispersion and no erosion, but at higher shear stresses, bulk erosion rates were similar to that of other waters and the portion of suspended load was near zero – the water remained milky white.

Erosion rates

Figures 7-6 and 7-7 show the measured erosion rates as a function of shear stress and time for the non-recirculating trials. They generally plot as straight lines on the log-log plots with the rate of erosion increasing approximately linearly with increasing shear stress (for most tests) and decreasing logarithmically with increasing time. Results from multiple regression analyses (as functions of shear stress and time) are presented in Table 7-4.

Figure 7-8 presents average erosion values from the recirculating flumes for Kc material. Figure 7-8a indicates on one hand that the chemistry of the eroding fluid is generally a second order effect on overall erosion rate, but recirculating the waters (allowing them to increase in suspended solids and ionic strength) causes erosion rates to be reduced by an order of magnitude at lower stresses (where dispersive erosion dominates) but only slightly lower at higher stresses (where bulk erosion dominates). Similar patterns were observed with the limed water.

The effect of initial compaction was not straightforward. The eroding water cut down through loose KC quickly, causing higher Manning's n values and higher shear stresses for given discharges and slope gradients, whereas very dense Kc produced more planar surfaces, faster velocities, lower Manning's n values, and lower shear stresses. Both loose and dense Kc swelled, but loose Kc swelled more quickly. The end result was that the erosion rate as a function of measured shear stress was not greatly affected by initial density because of these compensating mechanisms, though the flow characteristics (especially velocity) was strongly affected. Very loose Kc at higher slope gradients, however, exhibited very rapid erosion as is often observed in mudslides.

The resulting values for Manning's roughness coefficient were high – 0.05 for the lab flumes and 0.15 for field flumes (see next section) – near the upper limit for very rough channels (treed floodplains (Chow, 1959)). While Manning's equation was developed for steady uniform flow, most of the laboratory flumes and all of the field flumes exhibited non-uniform, unsteady flow with frequent sills and plunge pools, rapidly changing flow depths and Reynold's numbers, and in the field, considerable meandering. Because flows are generally very shallow, the relative roughness of the bed is both high and variable. Use of Manning's equation with an average Manning roughness coefficient for modelling flow is even more empirical than the basis under which the equation was originally fit (see Manning, 1890; Fischenich, 2000) but as shown below, provides a useful empirical tool for estimating erosion.

7.7 Field flumes

Field flume tests were performed on an bare (uncapped, unvegetated), 60m long planar in situ slope that had been regraded several months before (Figures 7-9 and 7-10). Two sets of tests were run – 3-m long in situ flumes that provided a direct comparison to the laboratory scale, and 40-m long rills somewhat more indicative of natural field conditions. The field test procedures were similar to those in the lab with differences noted below. The source materials for the laboratory Kc flumes were taken from the surface of the area hosting the 3-m and 40-m in situ field flumes.

Methods

To construct the 3-m flumes, two 3-m long parallel plastic strips (lawn edging) were pushed to a 10-cm depth into the clay fill to make flume dimensions similar to those in the lab. Flumes were set out in a radiating pattern on a planar slope to create tests at different slope gradients. A small diffuser was used to create even flow across the flume at the discharge. At the distal end of each flume, a small pit was dug and a small sheet metal chute was pushed into the clay to allow water sampling and to minimize headcutting.

For the 40-m flumes, five 20-cm wide by 20-cm deep troughs were dug into the slope adjacent to the 3-m in situ flumes various orientations to provide different slope gradients. The soil was tamped by hand afterwards and left for several weeks to weather. An additional test was run down an undisturbed natural sinuous rill of similar dimensions. Reading locations were set at 1 m, 8 m, 16 m, 24 m, 32 m, and 39 m. A similar pit/chute system at the base of each flume for sampling as described above was used.

The 3 m tests were run simultaneously on a warm sunny day in July 2000 and the 40-m long tests were performed the following day in similar weather.

Results

Visual observations

Observations in the field matched those in the lab with several important exceptions.

The initial clay surfaces in the field were slightly looser and drier than those in the lab, with more variability in material properties down the flumes (especially for the 40-m flumes). Despite the care taken, there was more initial topographic variability in the field than in the lab.

The 3-m in situ flumes showed deeper and faster downcutting than experienced in the lab – with four stairs forming in the steeper flumes. Tunnelling under the flume sides was a continuous problem needing maintenance throughout the test. Downcutting of 4 to 8cm over five hours was seen in the steeper flumes. The deeper downcutting, narrower flow width and tunnelling seen in the field flumes are likely indicative of a looser material with a network of dessication cracks which was obliterated in laboratory flume tests.

Flow down the steeper 40-m flumes was also marked with more downcutting than seen in the lab, and a greater tendency for meandering on the steeper flumes. There were also reaches with large intact glaciolacustrine clay (Pl) lumps that were more erosion resistant than areas of the flume dominated by Kc fill.

The 40-m flume that re-occupied a natural rill showed similar results to the other steep 40-m constructed flumes, but there was increased topographic diversity, more meandering, and some undercutting of the outside bends of meanders.

Results from the two 40-m long, low slope gradient flumes were disappointing. Flows required hours to reach the far end of the flumes due to water pooling and infiltrating into the fill. Erosion rates measured at the end were very low, partially due to redeposition of eroded materials in still shallow pools along the flume. Conductivities of the water were also high, reducing erosion and favouring redeposition. Testing using average shear stresses less than about 5 Pa, that had proved easy in the lab, was impractical in the field.

Erosion rates

Erosion rates for the field flumes are shown in Figure 7-11 and summarized in Table 7-4. Erosion rates in the 3-m flume were approximately a half to one order of magnitude greater than those from the 40-m flumes which also showed greater scatter. The difference is thought to be due to greater rates of in channel sedimentation in the 40-m flumes and the higher percentage of dense blocks of Pl clay (material variability) in the 40-m flumes. While erosion rates of the recompacted Pl clay tested in the lab were similar to those of the Kc materials, the Pl materials in the 40-m flumes were visibly less erodible than the adjacent Kc materials.

7.8 Comparison of laboratory and field test results

Flows and erosion rates

Figure 7-11a shows modest agreement between laboratory and field relationships between erosion rates and shear stresses, but the subtle differences are important in accuracy of predictions.

Water flow in the field flumes has a wider distribution of shear stresses due to more irregular topography – the staircase patterns are more irregular and more pronounced, and there can be significant in-channel deposition. As discussed above, the most significant difference was that the back-calculated Manning's roughness coefficient (0.10 to 0.25) for the field flumes was much higher than that from the lab, confirming field observations of increased roughness. The result is that velocities in the field tended to be clumped at the 7 to 15 cm/s range (Figure 7-11b), whereas in the lab they typically ranged from 5 to 45 cm/s. Manning's roughness coefficient may even be higher for more sinuous natural gullies.

Because the relationships between average erosion rate as a function of average shear stress and time from the laboratory and field data were similar, they were combined to create a single empirical relationship for Kc erosion that could be applied for modelling field behaviour (Figure 7-12).

Figure 7-13a and Table 7-5 indicates that using values purely from laboratory tests to predict erosion rates in the 40-m field flume tests results in an over prediction of field erosion rates by a factor of about 5 and use of pooled empirical coefficients for field and lab results in an average over prediction of field erosion rates by a factor of 1.7. While not dissimilar from published values, this outcome indicates that lab testing should not be the sole method to predict field erosion rates, as discussed below.

Water chemistry

Complicating the erosion of dispersive clays is the change to the eroding water chemistry during the erosion event or trial. The eroding water accumulates salts during the erosion process through initial washing of surface salts, leaching of salts from the in place material, and diluting the salts in the pore waters and from the clay surfaces of the suspended sediments. Some geochemical exchanges on the clays also occur. The rate of exchange is rapid but likely not instantaneous – some kinetic effects are likely involved.

Figure 7-14a shows changes in electric conductivity (EC) of the eroding water for recirculating flumes. In most cases, there is a rapid initial increase followed by a slowly steadily increasing concentration throughout the test. One exception is the lime tests, which decrease in conductivity with time, perhaps due to precipitation or other geochemical reactions.

Figure 7-14b shows the increase in conductivity along the slope during the in situ flume tests. Rates of increase are approximately linear with distance down the slope and the rate of increase starts very high initially (due to washing of salts from the dry salty surface of the deposit) and decreases with time, likely related to the decreasing erosion with time.

Table 7-6 shows how ionic contents of some water change during the recirculating flume tests. Distilled water increases in TDS to 1200 to 1650 ppm and increases in pH to 8. Tailings recycle water, already high in sodium and chloride ions, sees a similar increase in TDS, some ion exchange, and remains at pH 8.9. A simple ionic balance reveals that the salts in the eroding water are not just diluted pore water from the clays – they are a result of the effects of dilution, dissolution of any precipitated salts, removal of salts from the clays, and geochemical reactions such as ion exchange and perhaps salts generated during oxidation of the clays which contain pyrite.

The use of recirculated water is common in laboratory flume tests and for rotating cylinder erosion tests. Where active clays are involved, consideration of using fresh water throughout the test should be given to avoid the complication of water chemistry changes.

The amount of dispersion is related to the difference in water chemistry between the eroding water and that of the clays. Water that is running off a landform picks up some of the salts, especially where it is actively eroding soil, and particularly when it is eroding dispersive clay substrates (a negative feedback mechanism). The impact is that the erosivity of the water is higher at the head of the gully (where the water is also carrying the least sediment) and lower at the distal end, particularly during the first flush of water, and for very long gullies. This accumulation of salts in the water causes flocculation and deposition of the suspended solids (reducing off-site effects) but increases salt loading to receiving streams and wetlands. This loading also diminishes the effects of minor differences in the initial water chemistries for erosion testing.

Comparison with published erosion rates

Table 7-7 compares erosion rates from this test to those published in the literature. Many erosion rates reported in the literature are expressed as coefficients to specific statistical erosion formulas (e.g., RUSLE) and others express erosion as a function of natural or simulated rainfall or a specific catchment and cannot be simply converted into the shear stress formulation employed here.

Most laboratory erosion rate testing is based on a formation using time critical shear stress ($A = 1$) that is time independent ($B = 0$) (see references in Table 7-8). Under very carefully controlled conditions (steady uniform flow, steady erosion rate, no changes to topography causing local variation in shear stresses or velocities) measured erosion rates generally follow this model extremely well, with correlation coefficients (r^2) for ε versus (τ - τ_{cr}) greater than 0.9. Similarly high correlations are produced under these results using mixtures of dispersive clay and sand and testing dispersive clays with various water chemistries.

Many researchers have found that there is a critical shear stress, τ_{cr}, which divides slow dispersive erosion from bulk erosion (Chapuis, 1986). Above this threshold, most researchers have also found that $A \sim 1$ and for steady flow, $B = 0$ (i.e. there is no time dependency). Their formulation becomes…

$$\varepsilon = k\left(\tau - \tau_c\right) \qquad \text{Eq. 7-5}$$

The classic definition of critical shear stress is that which is needed to initiate movement for a given sized particle – thus, it varies for a non-uniform soil. Dispersive clays present a special challenge for this formulation because each sample has a mix of mineralogies and grain sizes (grading from fine clay to sand) and during erosion, they have continually changing particle size, dimension, density, and geochemistry. One result is that some particles erode under very near-zero shear stresses. Some authors define critical shear stress as that required to cause measurable erosion rate, erosion rate above some arbitrary threshold, or that for the onset of more rapid mechanical (or "bulk") erosion of particles.

For the clays tested in this survey, there is a transition from dispersive erosion to mass erosion that is better simulated by a continuous curve rather than an abrupt breakpoint, likely because of the different velocities and shear stresses at different points in the flumes, as well as the complicated dispersion and erosion mechanics.

By using this slope/intercept formulation, the critical shear stress for Kc can be estimated at about 2 Pa and the critical velocity about 15 cm/s (an average for the entire flume). The erosion rate coefficient, k, is approximately 1 to 2 kg/m^2/h/Pa. These are based on average flows for unsteady, non-uniform flow conditions in the flumes and roughly fit with values reported in the literature (Table 7-7).

Data from several studies are re-interpreted in terms of the erosion rate equation from this study in Table 7-7. Overall erosion rates from the present study are similar to those reported using similar clays, which span 7 orders of magnitude, with many rates falling between 1 and 10 kg/m^2/h for modest shear stresses. Comparing each of the coefficients to the erosion rate equation, A-values are similar at about 1 (ranging from about 0.9 to 1.4) indicating that the erosion rate varies approximately linearly with average shear stress. B-values for most tests are assumed 0 and erosion rates are often measured after the initial flush of loose erodible material is over. For tests where measurements are taken over time, B values of about –1.0 to +1.5 are noted and depend on the initial conditions of the shallow surface layer and any detritus that has collected in the gully. Patterns of decreasing erosion rate with time from watershed experiments are sometimes masked by variation in rainfall intensity and the rise and fall of the discharge hydrograph, but for small catchments patterns in the literature match those from the present study. Erosion rate predictions are usually dominated by the C coefficient, which typically ranges from 1.5 to 4.5.

There are two critical distinctions between tests – many are designed to provide uniform surface conditions and determine erosion (detachment) rates. Few, such as the present test include both detachment and in-channel deposition, and have a spectrum of shear stresses and erosion rates reported as averages. Watershed studies provide an averaged view, and include allowances for sediment deposition before measurement, highlighting the critical difference between erosion rate and sediment delivery rate. As always, modelling and testing need to be mated for the overall mechanics and analysis.

7.9 Comparison of test to field performance

To investigate rates of field erosion, a simple simulation was used. Weather data from the Environment Canada Fort McMurray Airport climate station was used 1991-1996 as a continuous record. A hydrology simulation program (HSPF) (Bicknell et al., 1997) was used to simulate runoff from a one hectare mature reclaimed forested watershed on a 10 percent slope on a 15-minute basis over the period of record (Figure 7-15). The model has been extensively calibrated for natural conditions at the Syncrude site, but only for much larger watersheds. The model takes into account snow and snowmelt, rainfall runoff simulation, and channel routing.

A simple erosion simulation using a spreadsheet was employed. For various gully slope gradients, widths and lengths, and Manning's roughness coefficients, the average shear stress was calculated (a rectangular cross-section was used). Based on the empirical erosion rate calculation and using the shear stress and time since flow started, an erosion rate was estimated and assumed to apply to the entire 15-minute interval. Net erosion from the gully was graphed and subject to sensitivity analysis.

In particular, it was assumed that the channel contained no vegetation or rocks (or no more than the few encountered in the 40-m flume tests). The pool-riffle nature of the test is assumed to be captured in the overall testing simulation and captured by an average (high) Manning's roughness coefficient of 0.15.

Extrapolation of data to very low flow conditions does not seem problematic as erosion rates at this end of the scale are very small and contribute little to the overall amount of gully erosion given ephemeral flows. It was assumed that Equation 7-1 could be extended to higher flows and shear stresses encountered during high intensity runoff events.

Results are presented in Figure 7-16. While no direct comparison of actual field erosion rates is yet available, examination of existing gully sizes and catchment areas is in general agreement with those predictions. That is, the volumes and depths of rills and gullies caused by concentrated overland flow in the study area are within about a half order of magnitude of those predicted here. A direct comparison is unavailable. A climate station is presently installed on the study area, and future erosion events will be studied to provide a better indication of how accurate the model is. Consideration of short-duration large-scale field tests is also planned.

7.10 Uncertainty in prediction

There seems to be a competition among modellers for the most encompassing and most accurate estimate of erosion. Many erosion models continue to be revised with more complicated features to handle specific aspects of erosion while at the same time being made simpler through the use of graphical user interfaces. There are many sources of error in the models and their parameters, and more especially in the inherent complexity and variability of natural and artificial deposits that can have profound effects on the results. This section briefly discusses some of the errors. While no model will ever be without significant error, these models provide means by which to bound the concerns and thus provide useful design information. Uses of the models are described below too. The most basic choice available to the modeller is whether to use a simpler model, or one that is more complex. It is not clear that the more complex models provide any better answers than a combination of simple modelling with expert judgement. The main pitfall to avoid is the use of the models for quantitative regulatory requirements.

Matching model and mechanism

Many of the models, such as RUSLE and WEPP are distributed models that do not model gully erosion – they are aerially based and fail to predict gully erosion. In most agricultural cases, maintenance can be employed to deal with gully erosion – the remainder is rill and sheetwash erosion that is a result of normal annual practices. These models could be employed to gully situations if there are large enough catchments that have a large number of gullies – the models could be calibrated to such conditions, using GIS. In practice, planning a high density of active gullies would be unusual. In most cases, the presence of gullies is more deterministic than probabilistic.

Erosion of dispersive clay fills needs to consider several mechanisms. Because these landforms are reclaimed and vegetated, inter-rill erosion due to raindrop splash or sheetwash is usually low and treated separately from the erosion of the dispersive clay substrate. In gullies, at low velocities, the dispersion of particles dominates the erosion, but overall erosion rates for gullies due to dispersion are low. Dispersion also causes a change in the grain size of eroded particles, allowing them to become more mobile. At higher velocities, larger flakes are carried as suspended or saltated load and more round particles roll and bound as bedflow. As velocities increase, erosion may occur by debris or mudflow causing slow to rapid downslope movement of large amounts of sediment. Erosion may lead to larger slumping or other landslides through a variety of mechanisms, mostly involving softening or rising water tables. No model can accommodate such a wide range of conditions – the engineer must deal with them in a decoupled fashion, often involving risk analysis or simply attempting to design out some of the failure modes.

Model uncertainty

Models are necessarily simplifications of the real world and thus there is model uncertainty. Attempts to overcome model uncertainty by adding more modules and complications are only partially successful in reducing uncertainty.

Parameter uncertainty

A common feature of uncertainty analysis is parameter uncertainty. Most of the individual measurement involved in field monitoring of erosion have significant coefficients of variation, often in the range of 30 percent. Measurement of bedload, suspended load, velocity, Manning's roughness coefficient, depth, widths, hydraulic radii, slopes, etc., are all subject to various amounts of error. The result is that individual measurements of erosion rate have considerable uncertainty, but some are negatively correlated, and the uncertainty in the final result is often less than that of the individual parameters.

Geometry

The geometry of flow is particularly important to modelling, but changes significantly during the tests, and during and between flow events. Gullies downcut, become more or less sinuous, interact with obstacles such as boulders or more resistant layers, revegetation may change the geometry, the gully headcuts and often forms an alluvial fan at the toe, or has in-channel deposition. The material properties change during testing – softening, dispersing, swelling. Materials from bank erosion fall into the channel during and between events.

Runoff

The amount of water reporting to a gully during an erosion event and over years is highly variable. In terms of climate, there is significant variation between each storm event, and from year to year. The landform and its vegetation may change the microclimate at the site and climate change may have an impact. Runoff characteristics can be highly variable – from changing watershed sizes and geometry (due to erosion, subsidence, and other effects), to changes in land use, fire cycles, vegetation succession and soil changes which especially effect infiltration and runoff. Modelling is complicated by snowmelt and frost effects on the soil. Spatial variations in snow thicknesses can have significant effects.

Soil properties

There is significant variation in soil properties – the most obvious being layering which is seldom uniform. The soil will see many biogeophysical changes, especially during its early life as a new soil. There is local heterogeneity. Dispersive clay soils have the additional complications of crusting, drying, freeze-thawing, swelling and other changes, including oxidation, leaching, and other geochemical changes. Perhaps the most profound effect is that of vegetation on the erodibility – rates of revegetation in eroding areas are difficult to predict.

Land use

In agricultural work, land use is one of the greatest factors in erosion. In most cases for mine areas that are being returned to natural systems, is that normal land uses are not expected to cause erosion. Logging, ATVs and other uses will impact erosion, as will any long term maintenance.

Other effects

Other effects on erosion rates include changes in water table locations, local or global geotechnical instabilities, effects of subsurface piping, irrigation, or subsidence leading to ponding and overtopping, erosion of shorelines or removal of fans by creeks, accumulations of salts affecting vegetation.

The big event

Whereas most agricultural or active mining/construction designs are interested in the 1 in 10 year event, designers and regulators for many mining landscapes are concerned about the 1 in 100 year event, 1 in 1000 year event, or even the probable maximum precipitation (pmp) event due to the longevity and potential consequences of residual hazards. Extrapolation of a few years of data to these large events, with compounding mechanisms (fire, drought, rains, earthquakes) is troublesome, especially where some of these events may be coupled.

Accuracy of individual tests

Table 7-5 and the Figures 7-6, 7-7, 7-11, and 7-12 indicate that there is considerable scatter in the present data – for example, at a given shear stress, the coefficient of variation of measured erosion values is typically 10 to 30 percent. The ratio of the upper to lower bound erosion rates varies from 2 to 6. The correlation coefficient (r^2) between predicted and measured erosion rates is generally 0.6 to 0.8. While some of this variation is due to measurement or other experimental errors and simplification of analysis, it is thought that most of the variation relates to the inherent sensitivity of erosion rates to subtle differences in material parameters, and local flow conditions.

For comparison, Table 7-8 provides an overview of variations in measured erosion rates versus various parameters (single dependent variables) such as slope angle, shear stress, time, gradient, etc from the literature. Coefficients of variation vary from about 10 to 40 percent and the ratio of upper to lower bound erosion rates is about 2 to 6 – very similar to those found in the present study. Both the coefficient of variation and the upper to lower bound ratio seem to decrease slightly with increasing scale – likely due to averaging effects over larger areas and the decreased sensitivity to measurement error.

Put in simpler terms, even when correlation coefficients are very high, there is considerable scatter of individual measurements of erosion rates as related to dependent variables. For example, for a given shear stress, the average erosion rate may be 1.0 kg/m^2/hr, but individual tests will generate values typically ranging from 0.4 to 1.6 kg/m^2/hr. This scatter needs to be considered in experimental design and in modelling.

Accuracy of modelling (predicted versus measured)
Table 7-5 provides some examples of how accurately the erosion of the 40-m field flumes is predicted by models calibrated to laboratory and field values. For instantaneous erosion rates, Figure 7-13 shows the measured versus predicted for models self-calibrated to the actual 40-m flume and based on 3-m laboratory data. There is a 1:1 relationship between the model and the observed for the field data (by definition since this was the calibration case) but of interest was the coefficient of variation of 40 percent indicating the high degree of scatter between measured and observed value. The instantaneous erosion rates predicted by the 3-m laboratory flumes overestimated the observed field conditions by a factor of 4.

Table 7-5 also compares the predicted total dry mass of eroded mass of dry solids over five hours in the 40-m field flumes compared to measured values. All predictions had a coefficient of variation of 15 percent (a reduction from the instantaneous rates due to averaging effects over the length of the test). The ratio of predicted to measured erosion varied from 0.8 for the field calibrated data set to 5 for the 3-m laboratory data. The combined field and laboratory dataset over estimated erosion by a factor of 1.7. Interestingly the model based on the recirculating data provided similar accuracy – but likely due to compensating errors rather than astute modelling.

While the mass of erosion can only be roughly predicted, the depth of gullies can be predicted with greater accurately because of geometry and some negative feedback mechanisms. The depth approximately varies as the square root of the eroded volume per unit length – gullies incise quickly when the volume per unit length is low, then much more slowly with depth. (If gullies are actively head-cutting, erosion rate prediction is even more difficult). After the initial erosion, the gully geometry may be closer to regime conditions for future events, which will reduce the erosion rates. Deeper erosion brings more of the capping material down into the base of the gully, which is usually less erodible than the substrate and usually encourages revegetation which greatly slows erosion. The downcutting may also concentrate boulders in a lag at the base of the channel which may help to limit downcutting. Gullies tend to attract more interflow and less evaporation, and the enhanced moisture conditions also help to support vegetation. Downcutting at the head of the gully and fan deposition at the toe also reduces the overall gradient.

The result is that provided that catchment areas are small, gullies on Kc materials in the oil sands region often tend to stabilize at depths of between 1.0 and 1.5m within several years of initiation.

Provided measures to accept and accommodate such gullies are in place, they can add to the landscape diversity.

Similarly, estimates of depositional fan size are also more accurate than that of volume, since the radius of the fan varies approximately proportionally to the cube of the volume. The fan grows in aerial extent quickly at first, but slowly thereafter.

The result is that for estimating rates of erosion (by mass or volume), even given very well-calibrated models, results for specified runoff events will generally vary from 40 to 160 percent of that predicted. Models for larger watersheds over longer periods of time are likely more accurate. However, few models are well-calibrated (virtually none outside of research areas), and may overestimate or underestimate erosion by a factor of five to ten. For watersheds that show marked threshold sensitivity (especially to infiltration, gully initiation, or tractive shear stress) errors in prediction of volumes of an order of magnitude is not uncommon. Even with this high range of uncertainty, upper and lower bounding of gully depths and fan radii is still useful.

7.11 Extrapolation to reclamation performance

Based on the form of the results in Figure 7-16 and observations of field performance, the following is suggested to estimate performance:

- Based on natural drainage spacing in the region, one might expect gullies at a spacing of about 200m – 600m. In anticipation of this spacing, the landform should be designed with this spacing in mind with swales at this spacing. Otherwise, the probability of gully initiation at this spacing should be considered high.
- Despite the best intentions, there is a certain probability of failure of these swales or a gully forming in unprotected areas – this can be estimated. Initial probabilities are high, but can be accommodated with maintenance (by over repairing gullies). The bathtub model for engineering reliability through time (Harr, 1987) showing higher probability of failure during the break-in period and the worn-out period, provides a useful conceptual model – failures are most likely to come in the initial years or during an extreme event (hopefully) far in the future.
- Estimates can be refined based on design storms and catchment areas, but in general, one should expect a few long gullies with steep sides to depths of 1 to 2m and fans at the toes of

20 to 30m radius. Sediment rates can be estimated. Some fraction of the eroded material will be carried (along with salts) to receiving streams, but the vast majority will be on-landform erosion and deposition.

- The most likely location for gullies is area of swales imperfectly designed or constructed, and especially at the intersections of landform elements, land uses, or reclamation techniques.

7.12 Designing for erosion and with uncertainty

The most important step for design is the setting and declaration of goals that are reasonable, performance based, realistic, and achievable (McKenna, 1996). Recognition of the inevitability of erosion, including gully erosion, is a critical first step. Avoiding linking compliance to numerical models or other prescriptive elements is essential for successful reclamation. A hierarchy of goals may need to be set – unacceptable off-site impacts is often one of the most important goals.

The first method of design is avoidance. In design and construction, one should ensure that every drop of runoff has a safe way to make it to the receiving stream. Random ponding of water should be avoided where it can overtop and initiate water erosion. Designs need to take into account changes such as land use, subsidence, and vegetative and animal effects. Plateaus should be drained down constructed waterways (usually down the old haul ramps). Benches should be omitted or tipped dramatically downslope (i.e., outwards) to avoid ponding water, and except where necessary, tipped back and laterally to gather and transport water to armoured downslope swales. Watersheds are kept small and distinct so that they don't change in size and the downslope areas can handle large events. Hillslope designs that mimic natural topography in the region (landform grading) should be employed to the extent practical (Schor and Gray, 1995).

Elements of self-healing (negative feedback) need to be incorporated – rock within fills that provides self healing, diverse vegetation and consideration of vegetation succession are critical (McKenna, 1996).

After proper design, risk assessment identifies areas of weakness and concern to which additional effort is placed. Secondary lines of defence are employed. Erosion rates are estimated, and the landform designed to accommodate erosion and deposition. Fans will often be in the 20 to 30m size for dispersive clays, up to 50 to 80m for larger catchments, so areas can be set aside to allow for their deposition without blocking streams. If substrates are not to be exposed (for example radioactive wastes), the covers need to be thick enough to stop the gully. Erosion rates can be estimated to allow sizing of receiving areas for sediments.

Ongoing monitoring and maintenance will often be required to meet all the goals, perhaps on a declining basis. Even with ongoing monitoring and maintenance, gullies will still occur during extreme events, but can be repaired later.

One of the common solutions for reducing erosion is to create slopes with lower slope gradients. But in the case of mining landforms, building shallower slopes will increase the catchment area and potentially increase runoff and erosion. Though it varies from site to site, there is usually a theoretical optimal steepness relative to erosion, and in some cases, short steep reaches will outperform long shallow reaches. Short steep areas must be separated by wide back-sloping and drained berms which catch sediment and reduce off-site deposition.

Balancing these (often competing) objectives is the need for rational judgement and tradeoffs. It is not useful to spend all of one's resources trying to reduce the last bit of erosion. Ongoing monitoring and maintenance is an important risk reduction mechanism, especially in the first few decades after reclamation when weakness in the erosion protection are likely to come to light. Early and robust repairs of unstable gullies will usually be required. Provision for allowance of stable gullies to remain as elements of diversity should be allowed. At some future point, risks may reduce enough to allow equitable transfer of the land back to the crown.

7.13 Improvements

Test methods employed in this chapter can be improved in several ways:

- Tests should avoid recirculating water when ever possible, due to the uncertainties that these add. Waters should have similar chemistry to those measured under natural conditions in the field.
- Tests should be focussed more on in situ field tests (rather than the lab)
- In the lab, greater attention to compaction, greater initial thickness of soil, and larger (10L) samples of discharge water may reduce some of the scatter.

- A more thorough mapping and analysis of existing gullies and rills, with particular attention to catchment areas, and through time, would provide useful information in calibrating future models.
- While full-scale field tests and monitoring can be rather involved, using existing gullies, and perhaps during real rainstorm events where practical is likely to provide the best estimates. Laboratory work can be used to investigate sensitivities and guide experimental design in the field.

7.14 Summary and conclusions

Erosion of constructed landforms, particularly those with highly erodible subsoils (or substrates) is one of the most common impediments to successful reclamation for two main reasons – expectations of no erosion or low erosion rates is usually unachievable, and the design of mining landforms in Canada does not usually consider surface-water hydrology and erosion explicitly. Elsewhere, design parameters are often prescriptive and may be ill-founded.

Models for predicting erosion for disturbed and natural land abound. When well calibrated, they may provide estimates that are within +/- 50 percent for known runoff events. More generally, partially calibrated models are accurate to within half to one order of magnitude for estimating erosion rates and volumes. In particular, reasonable modelling of gully erosion is presently unobtainable due to the numerous complexities, especially in the areas of modelling the interaction of climatic events, runoff, flow dynamics, erosion, deposition, and self-healing and revegetation. Predicting gully erosion requires a probabilistic assessment of gully initiation, followed by a coupled hydrology erosion model to predict rates of growth and sediment loss.

To better understand some of the dynamics and rates, a simple laboratory and field flume test procedure was developed for testing of moderate dispersive clay shale fills in the oil sands region. There was modest agreement between laboratory and field flume erosion rates for given shear stress and time. Rates and processes were similar to published values for dispersive clays. The actual mechanics of erosion are complicated, especially given the step and stair pattern of erosion seen in the lab and field, and the ever changing particle size and material properties of the eroding soil and changing erosivity of the water due to changing solids content and chemistry. Results from the laboratory flume tests over-estimated erosion rates for 40-m field flumes by a factor of 4 and combined field and lab parameters over estimated field erosion by a factor of 2. Coefficients of variation for laboratory parameters and predictions of field erosion are typically 10 to 40 percent and have ratios of upper to lower bound erosion rates of 2 to 6 which are similar to those in the literature.

A simple model that uses average shear stress, time and erosion rate equation applied to a rill or gully draining a one hectare watershed produced results that are similar to observed field performance, though a direct comparison is not yet available.

Even given the large range of uncertainty, the landscape engineer should use field derived or calibrated models to estimate erosion rates and design constructed landforms to both avoid and accommodate the inevitable erosion. Several strategies are presented. The landforms should be constructed in a series of very small watersheds, with armoured channels that direct water safely from the landform to the toe. Benches and other flat areas should be sized to allow deposition of eroded materials (to reduce off-site effects), but to avoid ponding water that can overtop adjacent slopes. Monitoring and maintenance for the first few decades as a minimum should be in place as a risk reduction mechanism.

Estimates of sediment fluxes are required for use in design and in communicating expected landscape performance. Simpler models, calibrated to local experience, similar to the one presented here, may be more useful than complicated process-driven or statistical models that may not handle the mechanics of erosion well. The models are best used to guide the landscape engineer's judgement. The landscape engineer needs to also deal with and communicate the inherent uncertainty in the landscape performance. The use of natural analogs is strongly encouraged.

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Table 7-1 Summary of index properties for unreclaimed surface material on SW30 dump

	Kca **(N=10)**	**Kc Mix** **(N=10)**	**Km** **(N=2)**	**Pl** **(N=7)**	**Overall mean & coefficient of variance**
Moisture content (%)	9-21 (range) 12 (mean)	5-17 11	8-12 10	5-20 12	11 31%
Liquid limit (%)	55-90 65	35-70 50	25-50 40	40-65 55	56 23%
Plastic limit (%)	18-24 20	16-20 18	19	16-22 19	19 10%
Plasticity index (%)	35-70 45	20-50 35	15-40 30	25-45 35	38 71%
Liquidity index	-0.25- -0.05 -0.20	-0.50 - 0.00 -0.25	-0.8 - -0.35 -0.55	-0.30 - -0.05 -0.20	-0.2 62%
Sand content (>60 micron) (%)	2-12 6	5-40 20	20-40 30	10-30 15	15 71%
Silt content (%)	35-50 42	35-45 40	40-45 40	35-45 40	40 12%
Clay content (<2 micron) (%)	45-60 50	25-55 40	20-35 30	35-50 45	44 24%
Activity	0.8-1.2 0.9	0.7-1.1 0.9	0.5-0.9 0.7	0.7 – 1.0 0.8	0.85 16%
Wet density (kg/m^3)	1520-2040 1870	1850-2125 1950	1875-2075 1975	1700-2075 1850	1900 7%
Dry density (kg/m^3)	1325-1850 1650	1600-1900 1725	1650-1825 1750	1500-1875 1650	1680 8%
Standard Proctor maximum dry density (kg/m^3)	1580-1675 1640	1575-1790 1700	1685-1860 1800	1560-1760 1650	1670 4%
Standard Proctor optimum moisture content (%)	19-23 21	15-24 18	11-18 15	16-23 19	19 16%
Relative dry density (% of Proctor maximum dry density)	80-118 100	95-109 101	98-98 98	93-109 99	100 7%

Table 7-2 Summary of index properties of materials tested in flumes

		Units	Kc Round 1	Kc Round 2	Kc In situ Flume	Marie's Kc	Pl Clay	Tailing sand
Base properties	pH		7.5	7.5	7.4	7.4	7.5	7.7
	EC	dS/m	16	12	14	15	6	0.4
	Organic carbon	%	1.2	1.5	1.4	1.2	1.3	0.0
	Soil CEC	cmol/kg	21	18	25	25	9	1.2
	Clay CEC	cmol/kg	45	50	55	45	40	15
	TDS		165	125	150	140	75	5
	SAR		13	18	14	15	6.4	1.4
Anions and cations water fraction	$HCO3^{-}$	meq/L	3	4	2	2	3	1
	$CO3^{-}$	meq/L	0	0	0	0	0	0
	Cl^{-}	meq/L	8	5	4	7	2	1
	SO_4^{--}	meq/L	155	120	145	135	75	5
	Total Anions	meq/L	165	130	155	145	80	6
	Ca^{++}	meq/L	23	21	22	21	26	2
	Mg^{++}	meq/L	56	21	46	37	20	2
	Na^{+}	meq/L	83	83	81	81	30	2
	K^{+}	meq/L	2	2	2	2	0.2	0.2
	Ba^{++}	meq/L	2	2	2	2	3	0.1
	$N\text{-}NH_4^{+}$	meq/L	0.1	0.1	0.1	0.1	0.0	0.0
	Total Cations	meq/L	165	130	155	145	80	6
	Total Salts	g/kg	11	11	11	11	3	0.2
Clay properties	Ca	meq/100g	4.0	4.7	4.2	4.3	5.0	0.2
	Mg	meq/100g	8.1	4.5	10.6	9.8	3.1	0.3
	K	meq/100g	0.7	0.6	0.9	0.8	0.1	0.0
	Na	meq/100g	4.4	1.0	5.8	6.5	0.4	0.2
	Total	meq/100g	17.2	10.7	21.4	21.4	8.6	0.8
	CEC		21	18	25	25	9	1.2
	ESP		21	5	23	26	5	15
Mineralogy	Smectite	%	70	60	80	80	40	0
	Mica	%	12	12	8	6	15	15
	Kaolinite	%	8	8	8	5	15	75
	Chlorite	%	5.0	8	2.5	5	10.0	5
	Vermiculite	%	trace	trace	trace	trace	trace	trace
	Qtz + Feldspars	%	2	2	2	2	5	5
Geotechnical index properties (USCS)	Liquid limit	%	58	50	54	74	29	NP
	Plastic limit	%	20	17	20	20	14	NP
	Plasticity index	%	39	32	35	55	15	NP
	Gravel	%	0	0	1	0	1	0
	Sand	%	12	19	12	4	41	90
	Silt	%	43	46	46	46	33	6
	Clay	%	45	35	42	50	25	4
	Activity		0.8	0.9	0.8	1.1	0.6	--
	Natural moisture content (m_w/m_s)	%	21	15	17	25	12	4
	Liquidity index		0.02	-0.08	-0.08	0.09	-0.14	--

Table 7-3 Summary of chemistry of eroding waters

	TW	WID	PP	RCW	CT	TW + lime
$HC0_3^-$	190	210	0	820	490	0
$C0_3^{-2}$	0	4	0	60	30	30
OH^-	0	0	0	0	0	2000
Cl^-	40	15	15	700	900	40
SO_4^{-2}	60	350	650	140	1550	50
Ca^{+2}	60	60	30	7	25	790
Mg^{+2}	15	30	13	10	35	0
K^+	2	5	10	10	25	2
Na^+	40	130	180	890	1400	40
Al^{+3}	10	10	30	0	0	0
pH	8.3	8.4	8.3	8.9	8.7	12
Electrical conductivity (dS/m)	0.5	1.0	0.9	2.8	4.2	3.2
Sodium adsorption ratio (SAR)	1.2	3.5	6.6	50	40	0.4
Exchangeable sodium potential (ESP)	0.6	3.8	7.6	40	35	-0.8

Key:

- TW = tap water (Athabasca River)
- WID = West Interceptor Ditch water (natural runoff)
- PP = Peter Pond water – water ponded on the SW30 Dump
- RCW = Tailings recycle water (process affected water from tailings pond)
- CT = Composite Tailings release water
- TW + lime = tap water that has been spiked with 3000ppm lime
- DW = distilled water (not shown in table)

Table 7-4 Erosion rates as functions of shear stress and time

Source data	Coefficient A (Shear stress coeff)	Coefficient B (Time coeff)	Coefficient C (Intercept)	Number of observations	Correlation coefficient r^2	Example erosion rate log ($kg/m^2/h$) *($kg/m^2/h$)*
All Kc	1.16 ± 0.08	-0.36 ± 0.09	2.69 ± 0.06	115	0.66	3.85 ± 0.12 *7.0 (4.0 - 12)*
Lab Kc	1.57 ± 0.06	-0.15 ± 0.09	2.63 ± 0.04	56	0.87	4.21 ± 0.10 *16 (10 - 26)*
Field Kc	0.98 ± 0.29	-0.54 ± 0.25	2.75 ± 0.08	59	0.51	3.73 ± 0.38 *5.4 (1.0 - 31)*
3-m Field Kc	0.83 ± 0.21	-0.42 ± 0.18	3.24 ± 0.07	32	0.61	4.08 ± 0.28 *12 (3.3 - 44)*
40-m Field Kc	1.39 ± 0.15	-0.47 ± 0.14	1.98 ± 0.09	32	0.81	3.37 ± 0.21 *2.4 (0.9-6.1)*
Marie's Kc	2.01 ± 1.06	0.04 ± 0.18	2.41 ± 0.10	30	0.83	4.41 ± 1.07 *26 (0.2-3600)*
Recirculated Kc	1.68 ± 0.16	0	1.96 ± 0.09	54	0.69	3.63 ± 0.18 *4.3 (1.9-9.9)*
Pl Clay	1.50 ± 0.09	-0.33 ± 0.14	2.63 ± 0.08	30	0.84	4.13 ± 0.17 *14 (6.2-29)*
Tailings sand	6.17 ± 0.13	-0.10 ± 0.58	2.20 ± 0.14	18	0.90	

Notes

- $\log(\varepsilon) = \mathbf{A} \log \tau + \mathbf{B} \log t + \mathbf{C}$, or
- $\varepsilon = \tau^A t^B 10^C$
- Erosion rate units = $g/m^2/h$, Shear units = Pa, Time units = hours, A,B,C dimensionless coefficients for use with units.
- ± x.xx indicates one standard deviation
- Example erosion rate is for (shear stress t= 10Pa, time = 1h) calculated from the above formula.
- Tested shear stress range is from about 0.5 to 20 Pa. Critical shear stress for clays about 1 to 3 Pa.

Table 7-5 Variability in measured and predicted erosion rates

This study	Type of test Parameters related	Correlation coefficient r^2	Ratio of upper to lower bound erosion rate for given dependent variable	Estimated coefficient of variation**
Measured erosion rate vs measured parameter				
Average erosion versus average shear stress at a given time	• Laboratory flume		2 – 4	10 – 30%
	• 3-m and 40-m field flume		3 – 6	25 – 35%
Predicted instantaneous erosion in 40-m field flume based	• Prediction based on equation fit to field ABC data from 40-m flume • Average prediction is 1x measured.		10	40%
	• Prediction based on 3-m lab ABC data • Over-predicts field behaviour by a factor of 4		5	35%
	• Prediction based on all Kc ABC data (lab + field) • Over-predicts field behaviour by a factor 2.5		5	35%
	• Prediction based on 3-m lab recirculating ABC data. • Poor fit to observed field data		10	40%
Predicted total dry mass of eroded solids over 5 hours from 40-m field flume	• Prediction based on simple model* fit to field ABC data from 40-m flume. • Average prediction is 80% of that measured.	0.9	2	15%
	• Prediction based on simple model* fit to 3-m lab ABC data. • Average prediction is 5x that measured	0.9	2	15%
	• Prediction based on simple model* to all Kc ABC data (lab + field) • Average prediction is 1.7x that measured.	0.85	2	15%
	• Prediction based on simple model* to 3-m lab recirculating ABC data • Average prediction is 1.8x that measured.	0.9	2	15%

* Model sums five hours of erosion at 15 minute intervals by calculating average d and τ to determine average $\varepsilon = \tau^A t^B 10^C$ using the average measured Q, and S for each flume trial and assumes w=0.10m and n=0.15 for all flumes.

Table 7-6 Effect of Kc erosion of eroding water chemistry

	Distilled water (DW) **After 5 hours**	**Distilled water (DW)** **After 5 hours**	**Tailings recycle water (RCW)** ***Initial***	**Tailings recycle water (RCW)** **After 5 hours**
Erosion test details				
Mass of sediment eroded, kg	7.1	3.6	3.7	
Volume of cycling water, L	55	47	43	
Discharge, lpm	25	30	30	
Number of cycles	140	190	200	
Equivalent flume length, m	425	575	600	
Anions (ppm)				
$HC0_3^-$	140	120	*820*	620
$C0_3^{-2}$	0	0	*60*	40
OH^-	0	0	*0*	0
Cl^-	50	20	*700*	690
SO_4^{-2}	970	700	*140*	960
Cations (ppm)				
Ca^{+2}	40	30	*7*	20
Mg^{+2}	40	30	*9*	40
K^+	13	11	*11*	20
Na^+	400	290	*890*	1150
Al^{+3}	0	0	*0*	0
Other				
Estimated TDS (ppm)	1650	1200	*2650*	3525
Lab pH	8.0	7.9	*8.9*	8.9
Electrical conductivity (dS/m)	2.1	1.6	*2.8*	4.7
Sodium adsorption ratio (SAR)	10.7	7.7	*52.2*	34.8
Exchangeable sodium potential (ESP)	12.5	9.0	*42.5*	32.8

Table 7-7 Comparison of erosion rates to values reported in the literature

Investigator	**Method and materials**	**Estimated equivalent erosion rate coefficient**		
		A (shear coeff)	**B (time coeff)**	**C (intercept)**
This study	Field and laboratory stepped flumes 0.2 x 2.6m, 0.2 x 40-m Channel and rill erosion (Dispersive clay fill)	1.15 0.8 to 2.0	-0.35 -0.5 to 0.0	2.7 2.0 to 3.3
Bryan and Campbell, 1982	Watershed erosion monitoring Badlands dispersive clays	Not measured (0)	Not measured (0)	-1.0 to 2.6
Cerda and Garcia-Fayos, 1997	Runoff during rainfall, sheet flow Badlands dispersive clays	Not measured (0) low gradient vs high gradient	low grad –1.2 to –0.3 high grad 1.0 to 1.4	low grad 0.9 to 1.6 high grad 3.8 to 3.9
Chapuis, 1986	Laboratory rotating cylinder Natural clays	1.0 to 1.4	0 (a zero value implies erosion rate is time insensitive)	1.6 to 2.0
Shaikh et al., 1988a	Pans in 2.5m lab flume 0.10 x 0.15m pans Channel flow Sand and dispersive clay mixtures	0.9 to 1.2	0	2.6 to 3.3
Shaikh et al., 1988b	Pans in 2.5m lab flume 0.10 x 0.15m pans Channel flow Dispersive and non-dispersive clays	1.0 to 1.15	0	1.9 to 3.9
Shainberg et al., 1992	Rainfall and mist simulations 0.3-m x 0.5m pan Sheet and rill erosion (Dispersive sandy loam)	Not measured	-1.8 to -0.3	Not measured
Torri et al., 1994	Field rain and rainfall simulation 10m x 10m Rill and pipe erosion (Dispersive silty clay and clayey silt badlands)	-0.3 to 0.2		4.6 to 5.5
Golder Associates Ltd, 1996	Channel flow in field flume Channel erosion (dispersive component) 0.5m x 19m Dispersive clay (Kc)	0.9	0	3.4
	Dispersive sandy clay (Kc Mix)	0.9	0	3.3
	Glaciolacustrine clay (Pl)	0.75	0	3.4

Table 7-8 Variability in measured and predicted erosion rates reported in the literature

Study	Type of test Parameters related	Correlation coefficient r^2	Ratio of upper to lower bound erosion rate	Estimated coefficient of variation*
Measured erosion rate vs measured parameter				
Bennett, 1999	Lab flume test to measure headcut erosion Erosion rate vs stream power		4	30%
	Lab flume test to measure headcut erosion Runoff vs time		1.3 – 2	5 – 20%
Samad et al., 1995	Laboratory flume Erosion rate vs shear stress		3 – 6	25 – 35%
Shaikh et al., 1988b	Laboratory flume Erosion rate versus SAR		7	40%
	Laboratory flume Erosion rate versus shear stress		1.3	5%
Evans et al., 2000	Flumes in natural rainfall Erosion rate vs grain size		25	45%
Loch, 2000	Field rainfall simulation on flumes Erosion rate vs % cover	0.99	1 – 1.5	5 – 10%
Schroeder, 1987	Field rainfall simulation Erosion rate vs slope gradient	0.6 – 0.9	2	20%
Harvey, 1974	Gully monitoring with natural rainfall Erosion rate for various grain sizes		6	35%
Torri et al., 1994	Irrigated field gullies Erosion rate vs shear stress	0.2 – 0.55	1.5 – 3	10 – 25%
Hancock et al., 2000	Watershed monitoring of natural rainfall Erosion rate vs rainfall runoff	0.85	2	20%
Wells, 1982	Aerial photo analysis Deposition fan size vs watershed size	0.91	3	25%
	Small watershed monitoring Erosion rate vs discharge	0.95	2	20%
Schumm, 1976	River watershed monitoring Sediment yield vs time		2	15%
Model prediction vs observed				
Heilig et al., 2001	Laboratory rainfall simulations Prediction of calibrated theoretical model vs measured lab erosion rates	0.85 – 0.97	1.5 – 2	5 – 15%
Sheridan et al., 2000b	Lab flume and rainfall simulation Prediction with multiple regression of soil parameters vs measured lab erosion rates	0.65	10	40%
Schroeder, 1987	Field rainfall simulation Prediction by equation vs measured field erosion rate	0.51	3	20%
Romkens et al., 1977	Field Rainfall simulation Prediction by RUSLE K values from multiple regression of soil parameters vs measured K in the field.	0.90	2	10%
Sheridan et al., 2000a	Laboratory flume and rainfall simulation Prediction by lab and model vs measured field sediment delivery rate	0.55	3 – 30	25 – 45%
De Roo and Jetten, 1999	Natural watershed monitoring, natural rainfall Prediction by calibrated model vs measured field sediment delivery rate	0.36	10	40%
Wu et al., 1996	Gully monitoring Prediction by model vs measured in field.		10	40%

* The coefficient of variation is defined as the standard deviation divided by the mean. For this simple analysis, the standard deviation is roughly estimated as ¼ of the range; the mean is estimated as the average of the maximum and minimum.

Figure 7-1 Study area: The 100 hectare SW 30 Overburden Dump at Syncrude's Mildred Lake Operation in northeastern Alberta (looking southeast) in 1999.

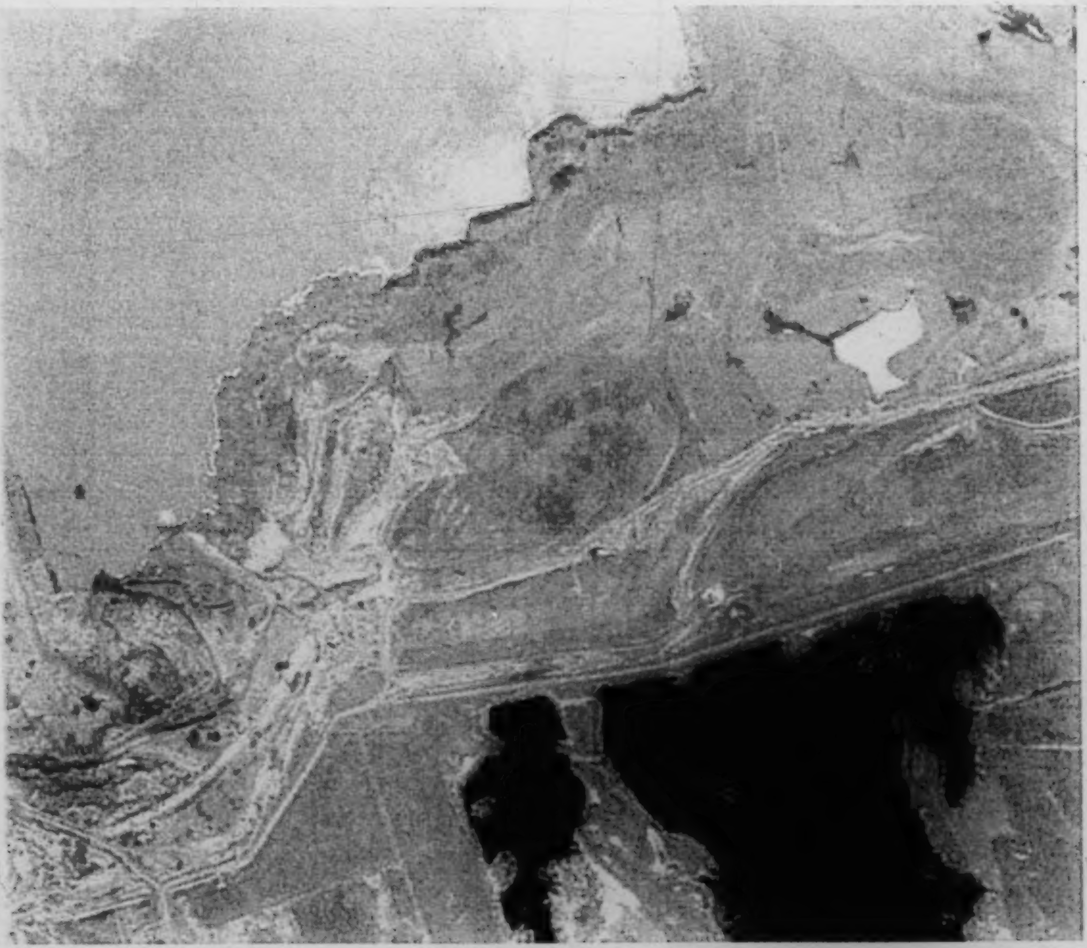


Figure 7-2 Photographs of the SW 30 Dump. A: Looking south. B: Looking southeast. C: A regraded slope before coversoiling. Note minor rills. D: Ten year old forested reclamation area on an adjacent constructed landform.

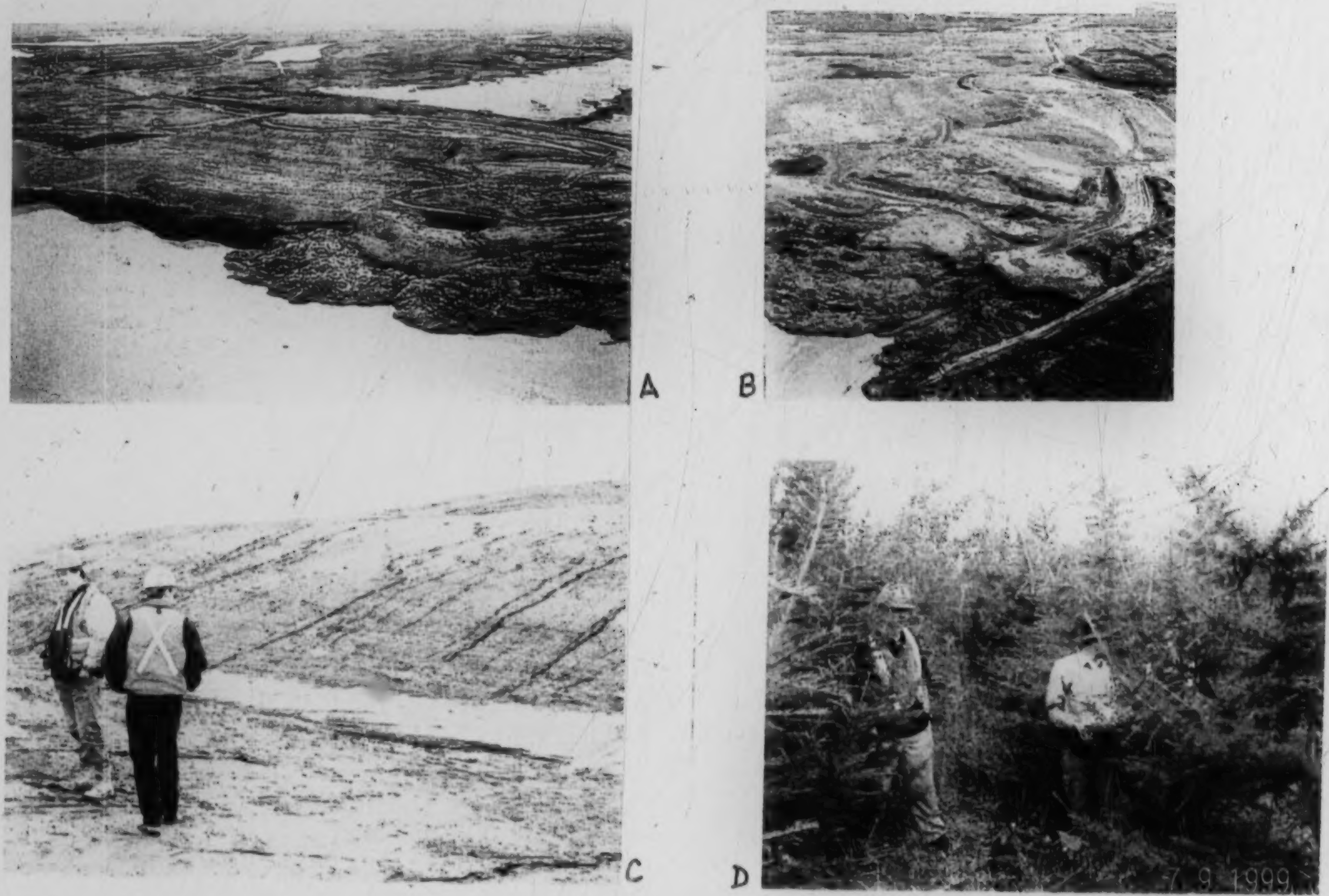


Figure 7-3 Distribution of material index properties of dump surface just prior to reclamation.

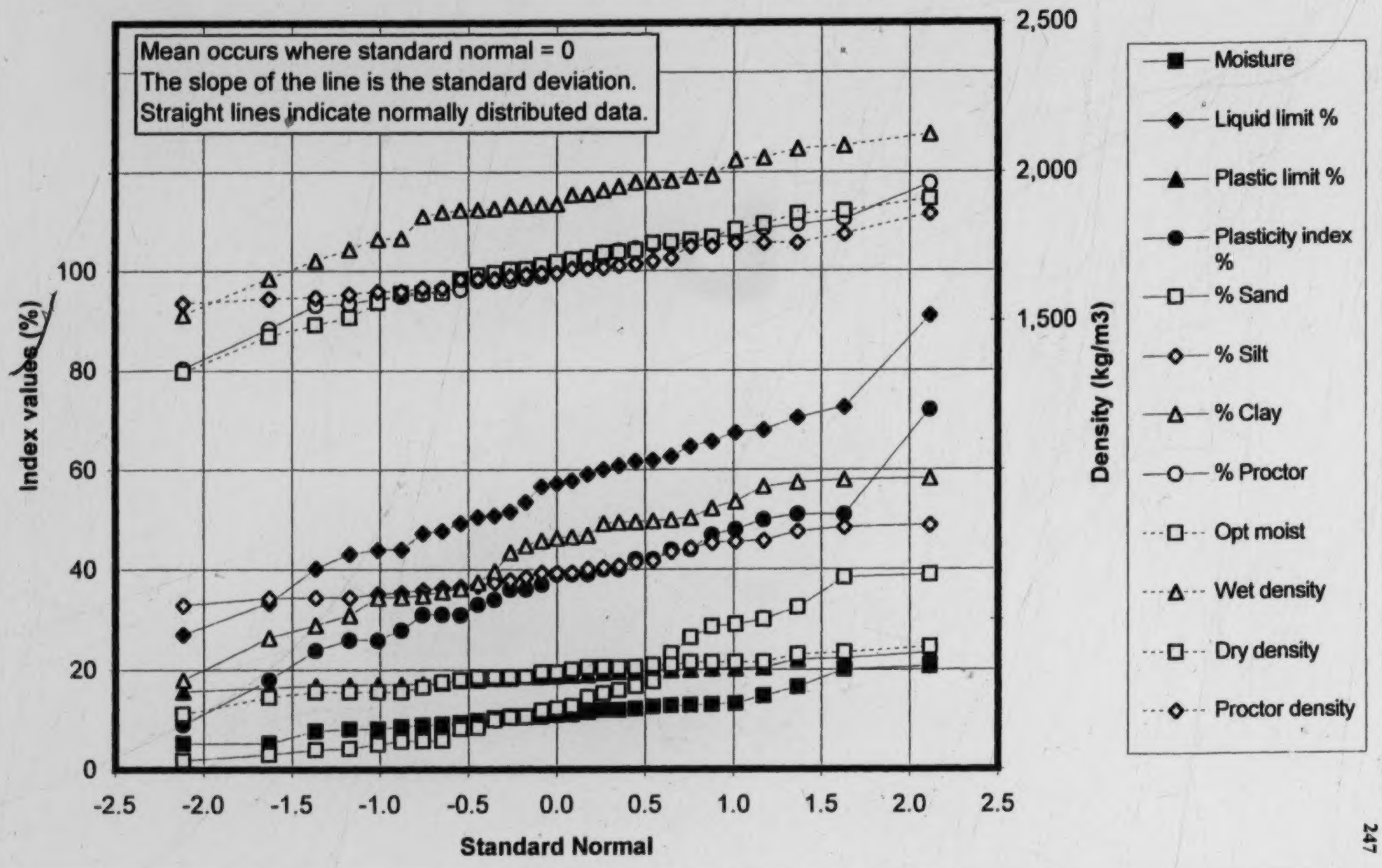


Figure 7-4 Susceptibility of tested materials to dispersive erosion based on Sherard's diagram.

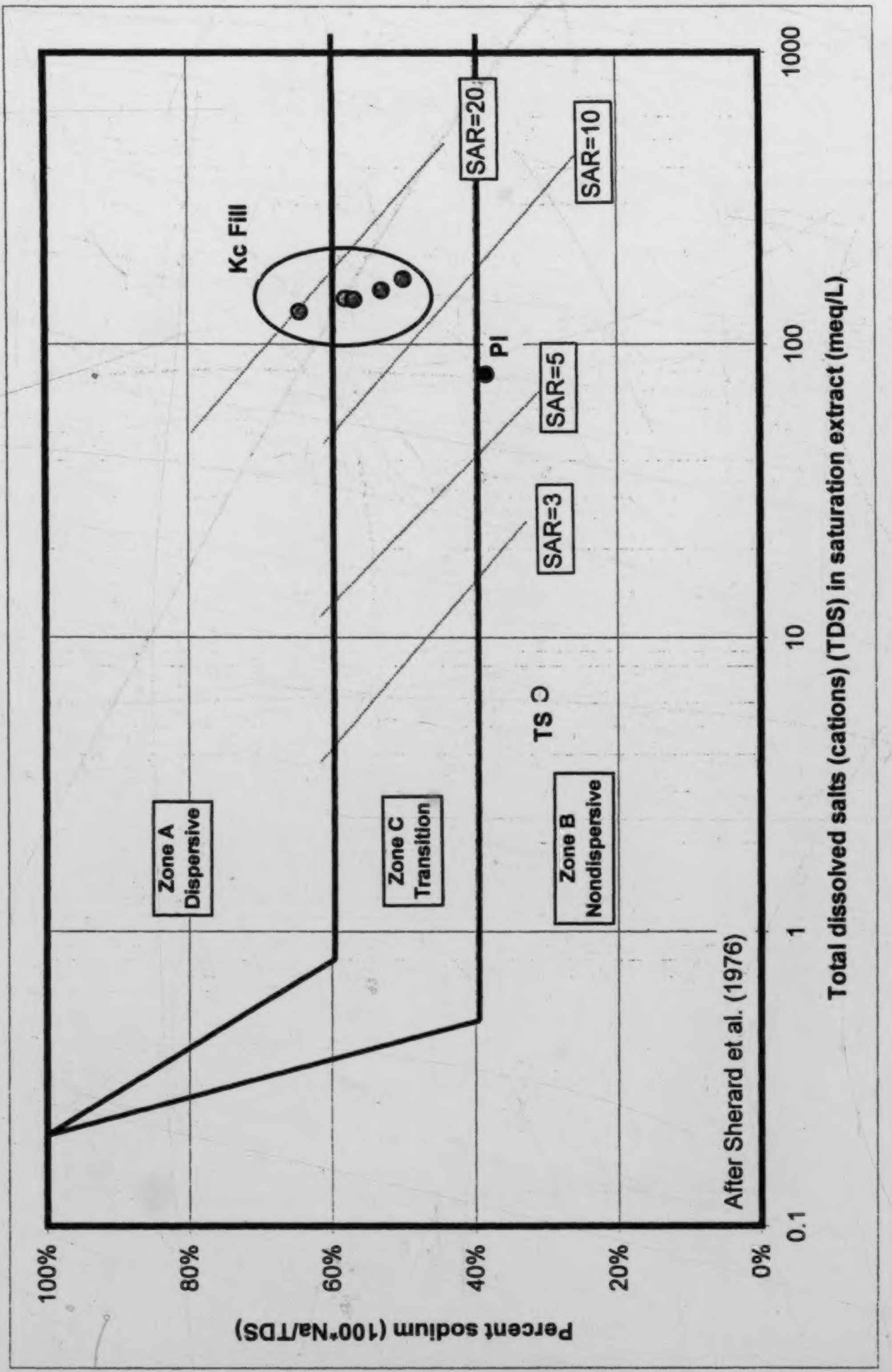


Figure 7-5 Schematic of 3m laboratory erosion flume and photograph of 6 trials in progress.

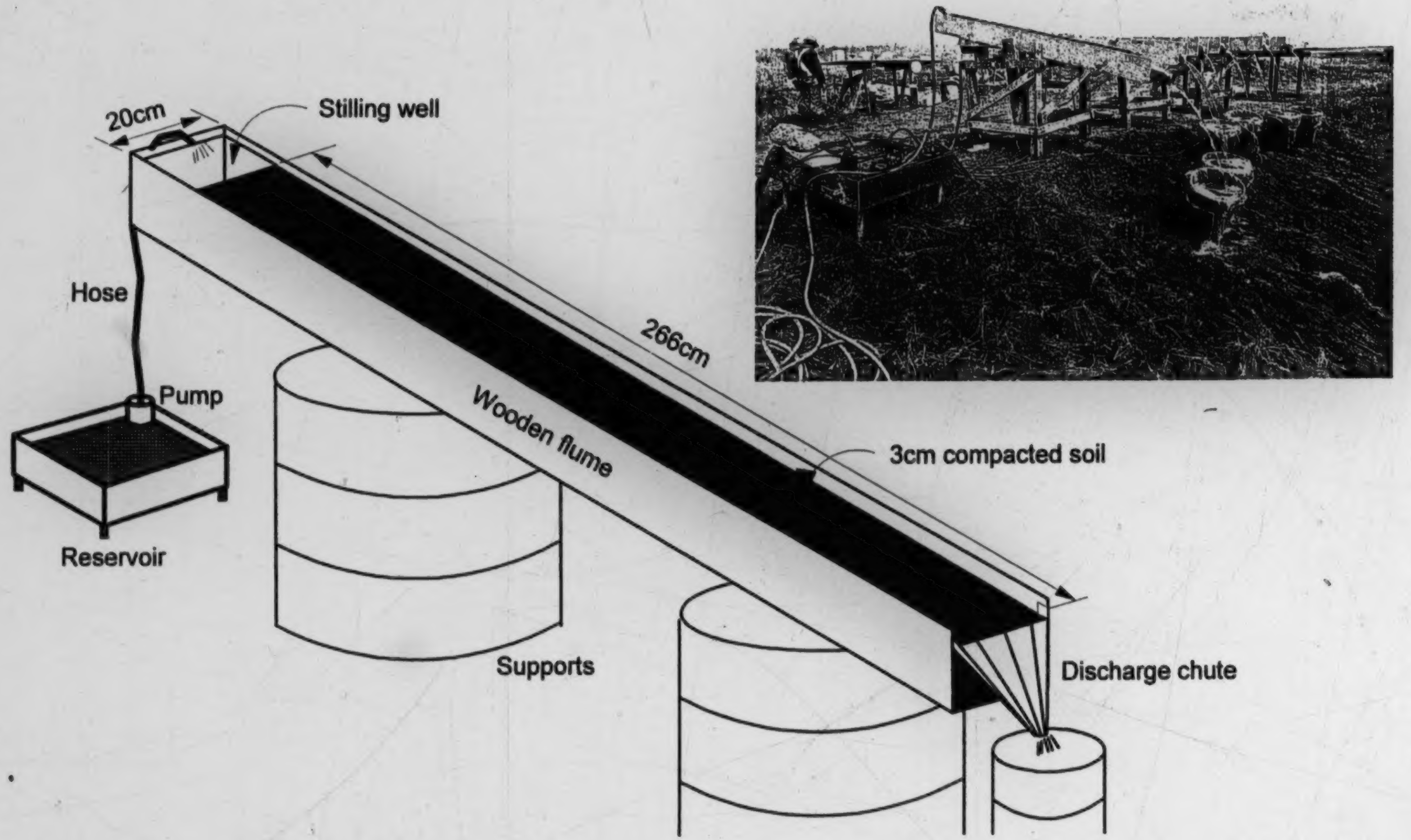

20cm
Stilling well
Hose
Pump
Reservoir
266cm
Wooden flume
3cm compacted soil
Supports
Discharge chute

Figure 7-6 Measured erosion rate as a function of shear stress

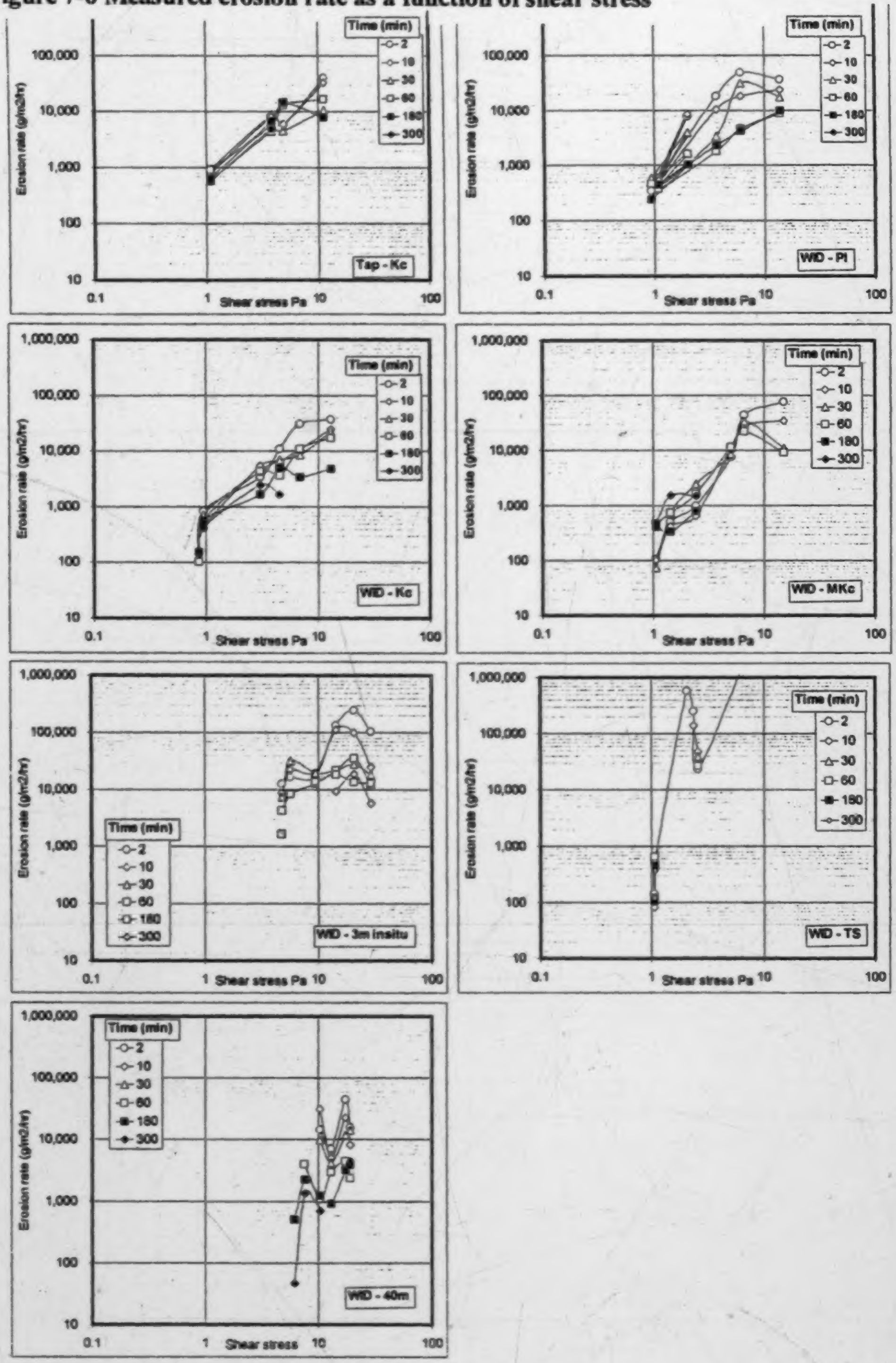


Figure 7-7 Measured erosion rate as a function of time

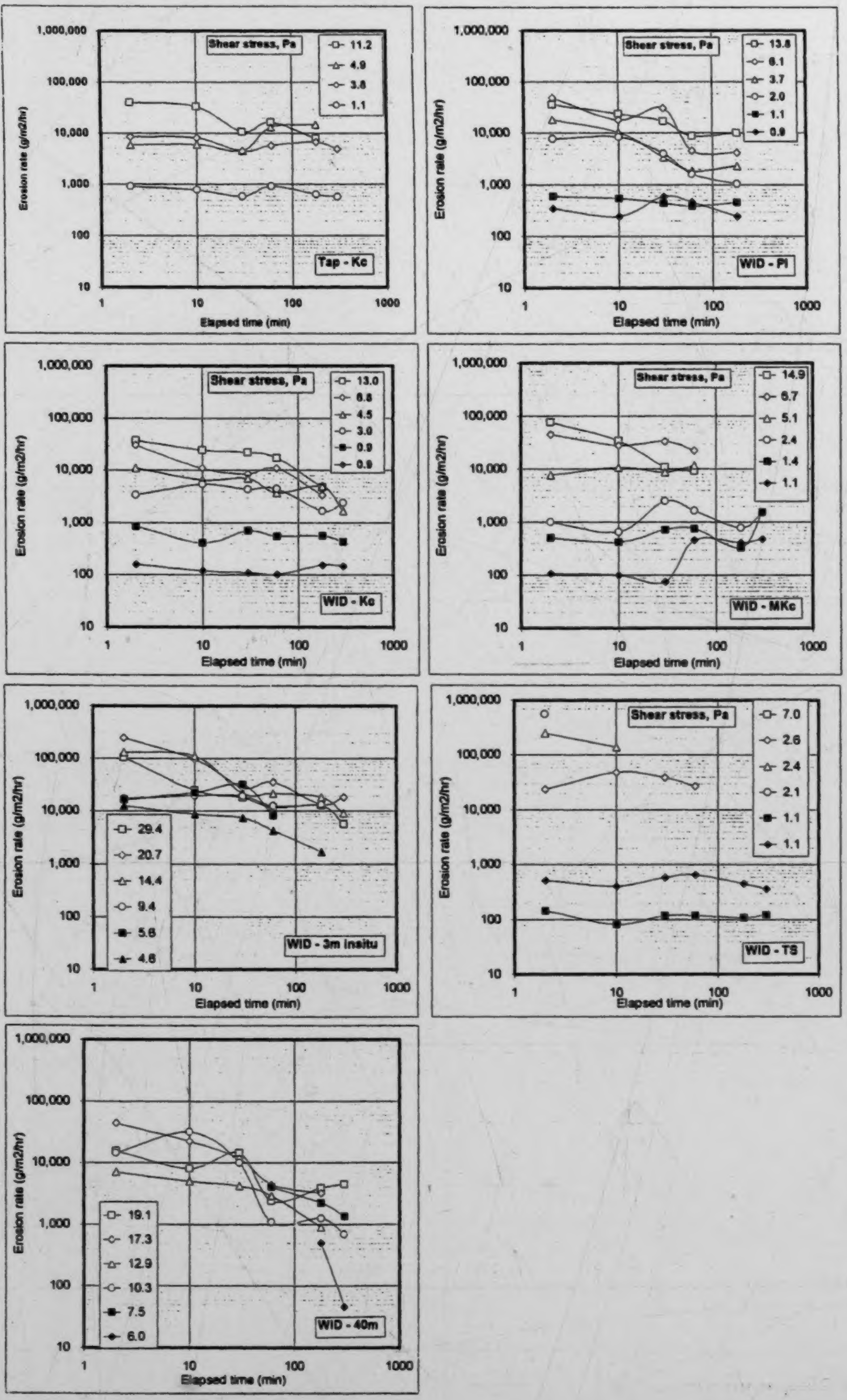
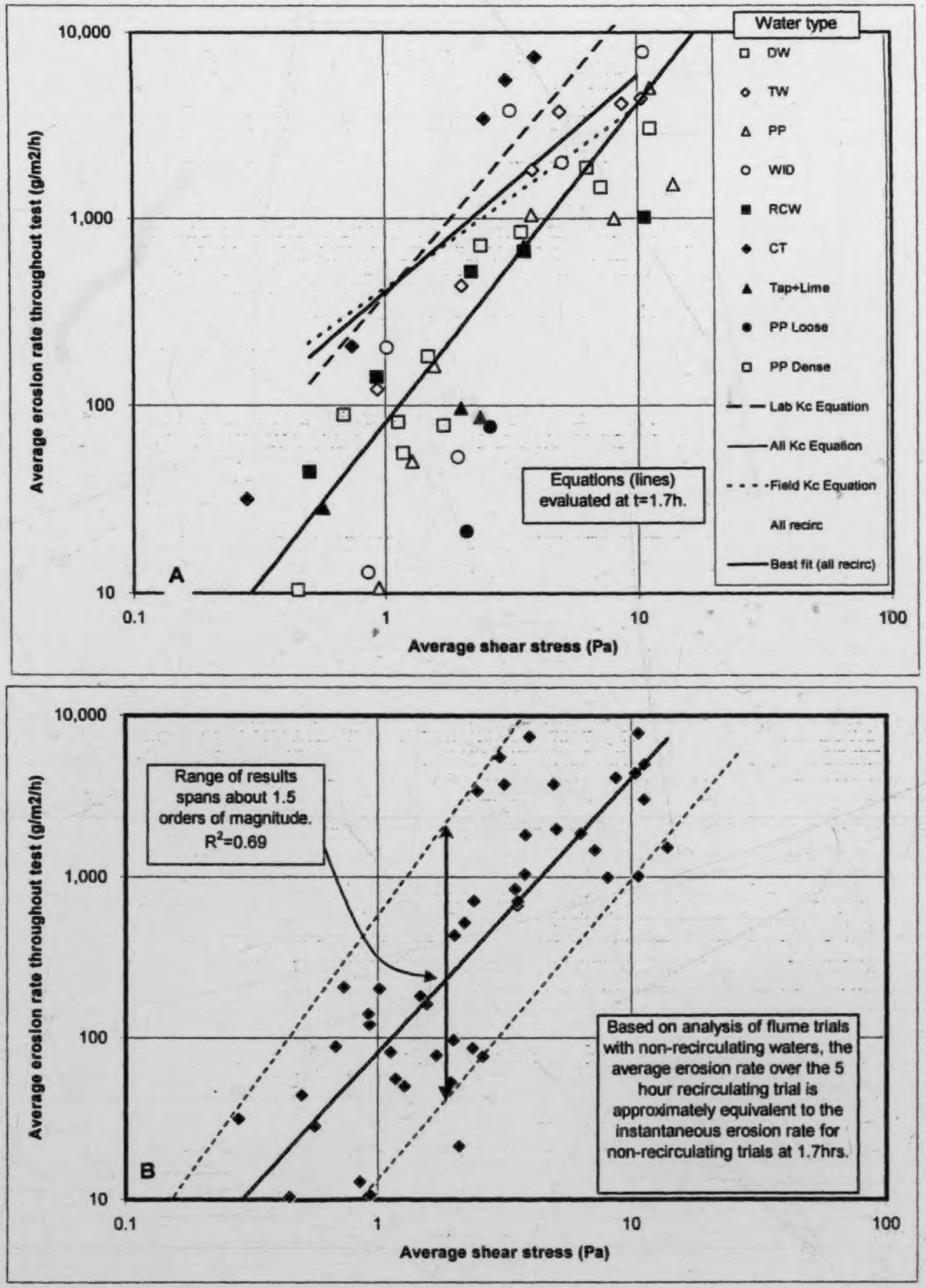


Figure 7-8 Erosion rates for recirculating laboratory Kc flume trials



Equations (lines) evaluated at t=1.7h.

Range of results spans about 1.5 orders of magnitude. R^2=0.69

Based on analysis of flume trials with non-recirculating waters, the average erosion rate over the 5 hour recirculating trial is approximately equivalent to the instantaneous erosion rate for non-recirculating trials at 1.7hrs.

Figure 7-9 Schematic of 3m and 40m field erosion flumes at SW 30 Dump.

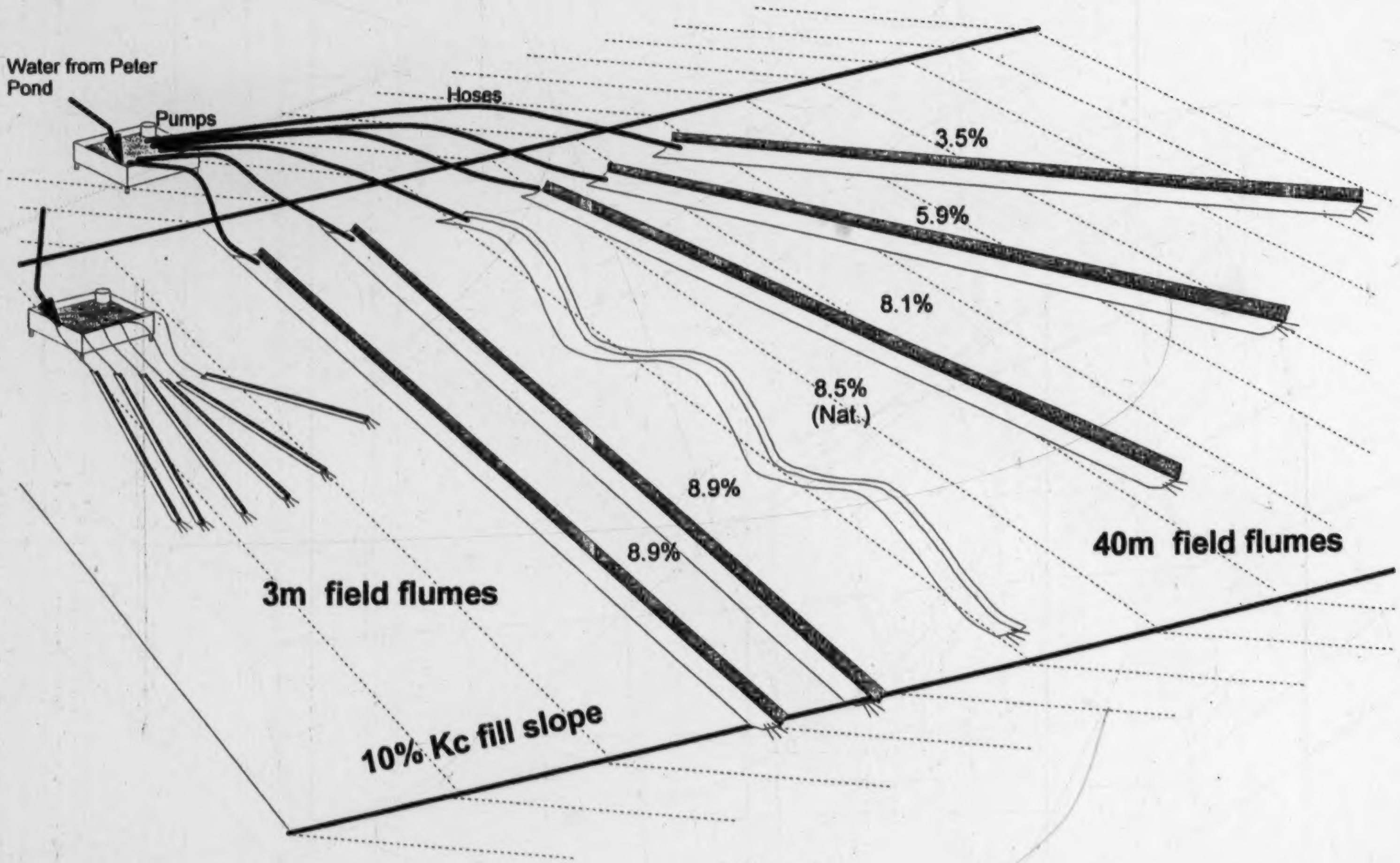

Water from Peter Pond
Pumps
Hoses
3.5%
5.9%
8.1%
8.5% (Nat.)
8.9%
8.9%
40m field flumes
3m field flumes
10% Kc fill slope

Figure 7-10 Photographs of flumes. A: 3m Laboratory flume. B: 40m insitu field flumes prior to test. C: 40m insitu field flume during test.

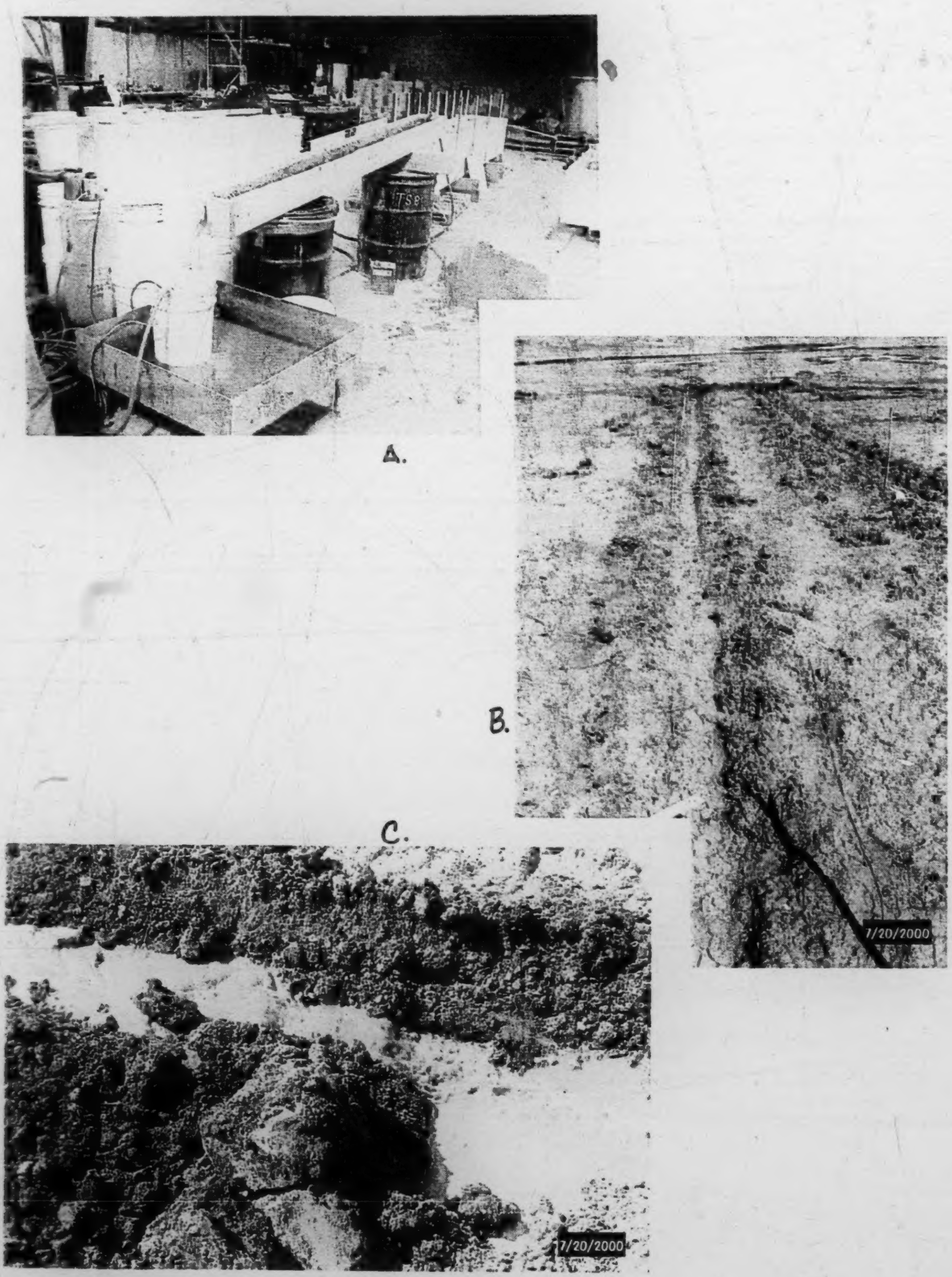

A.
B.
7/20/2000
C.
7/20/2000

Figure 7-11 Erosion rates versus shear stress and velocity for lab and field trials.

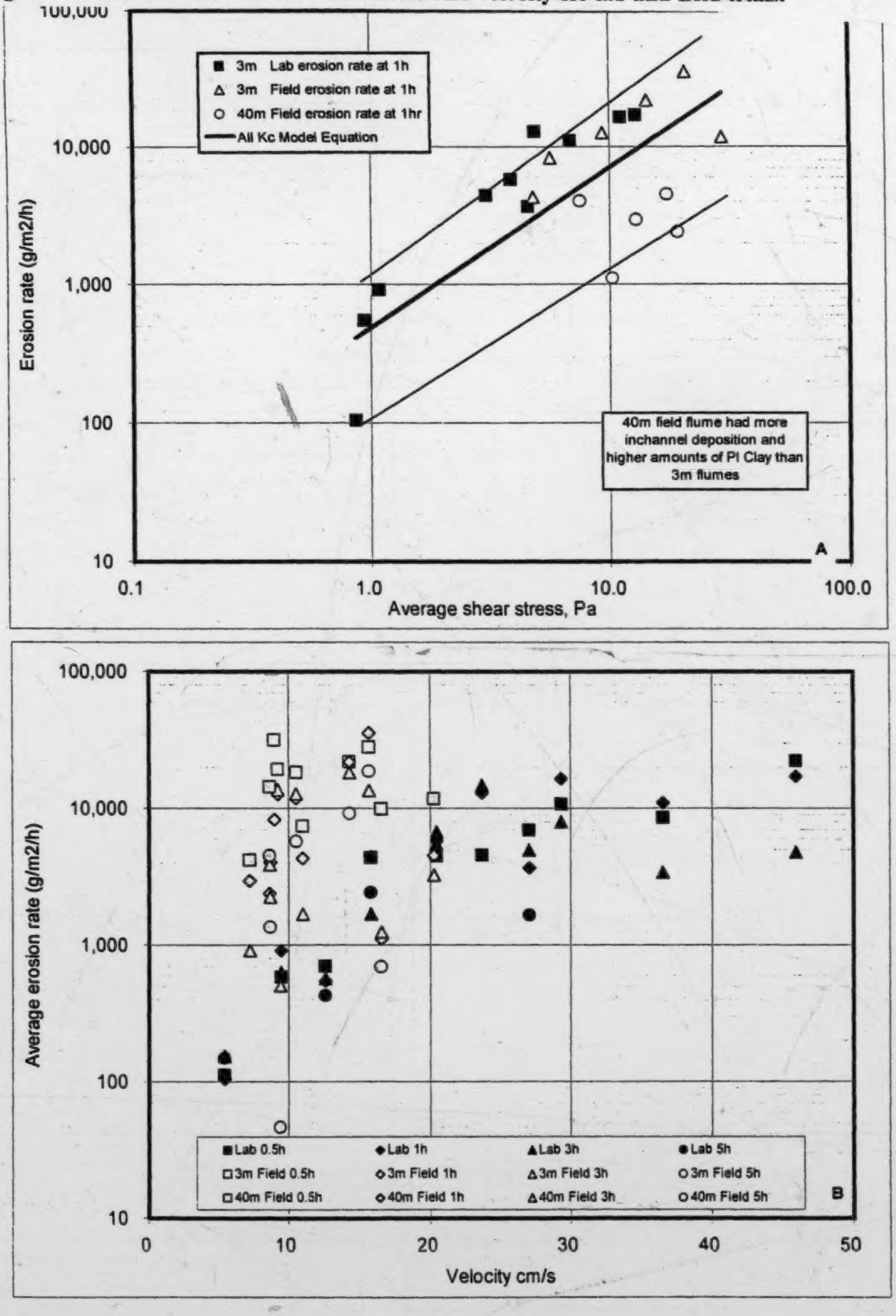


Figure 7-12 Combined erosion rates from lab and field flume trials for Kc

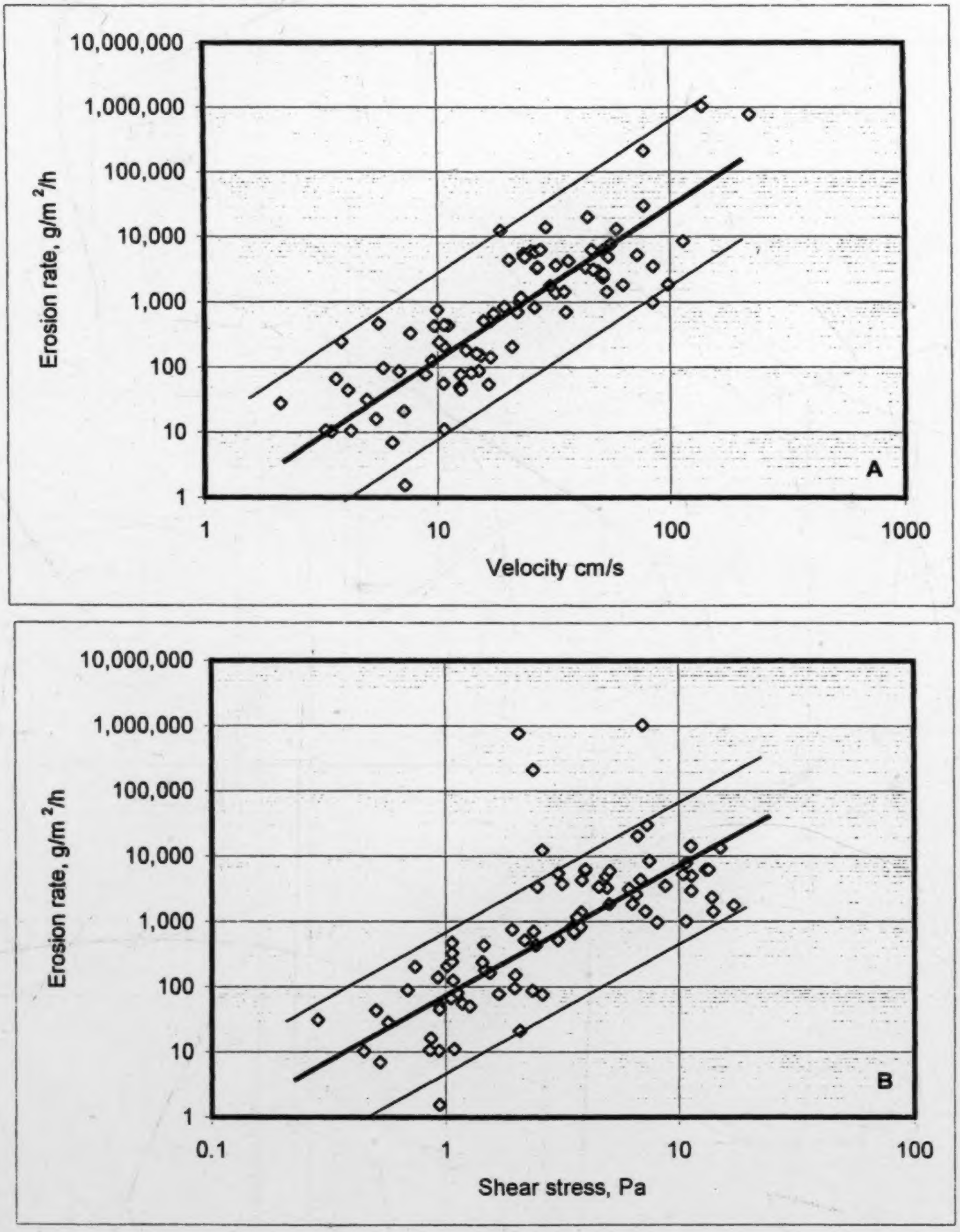


Figure 7-13 Comparison of predicted versus measured erosion rates for 40m Kc field trials

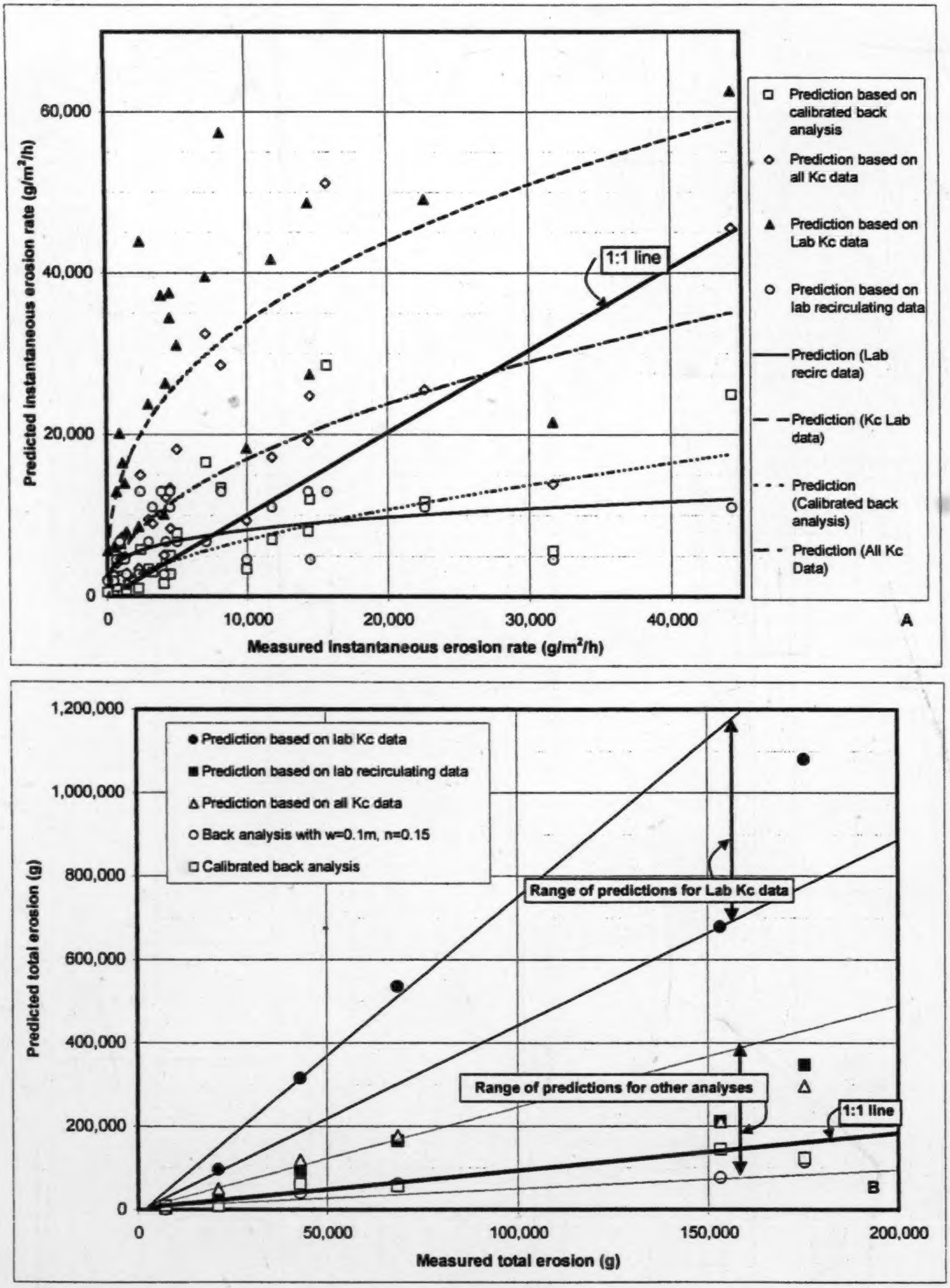


Figure 7-14 Change of water chemistry during erosion trials. A: Recirculating laboratory flumes. B: Non-recirculating field in-situ flumes.

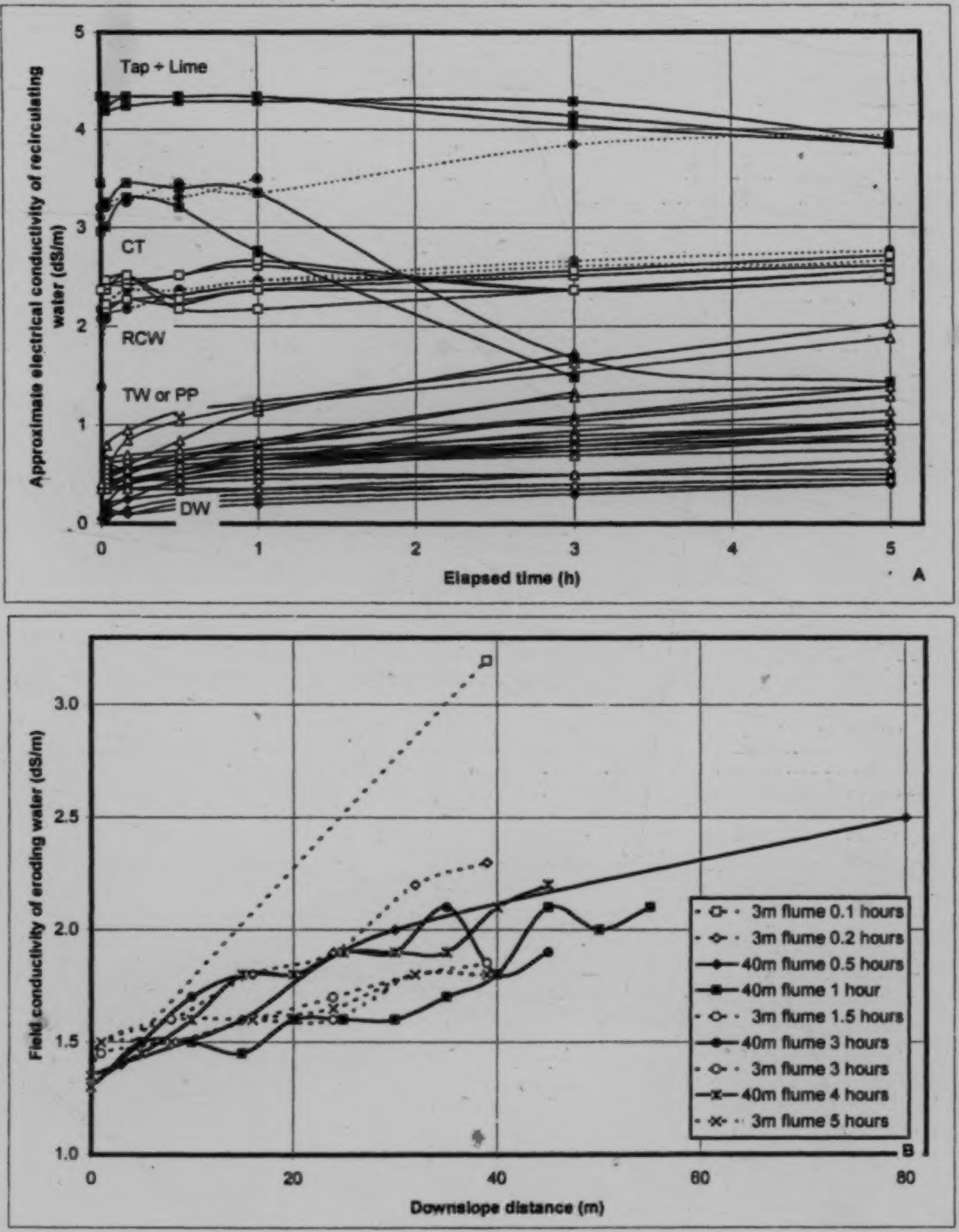


Figure 7-15 Runoff simulation based on local climate data 1991-1996.

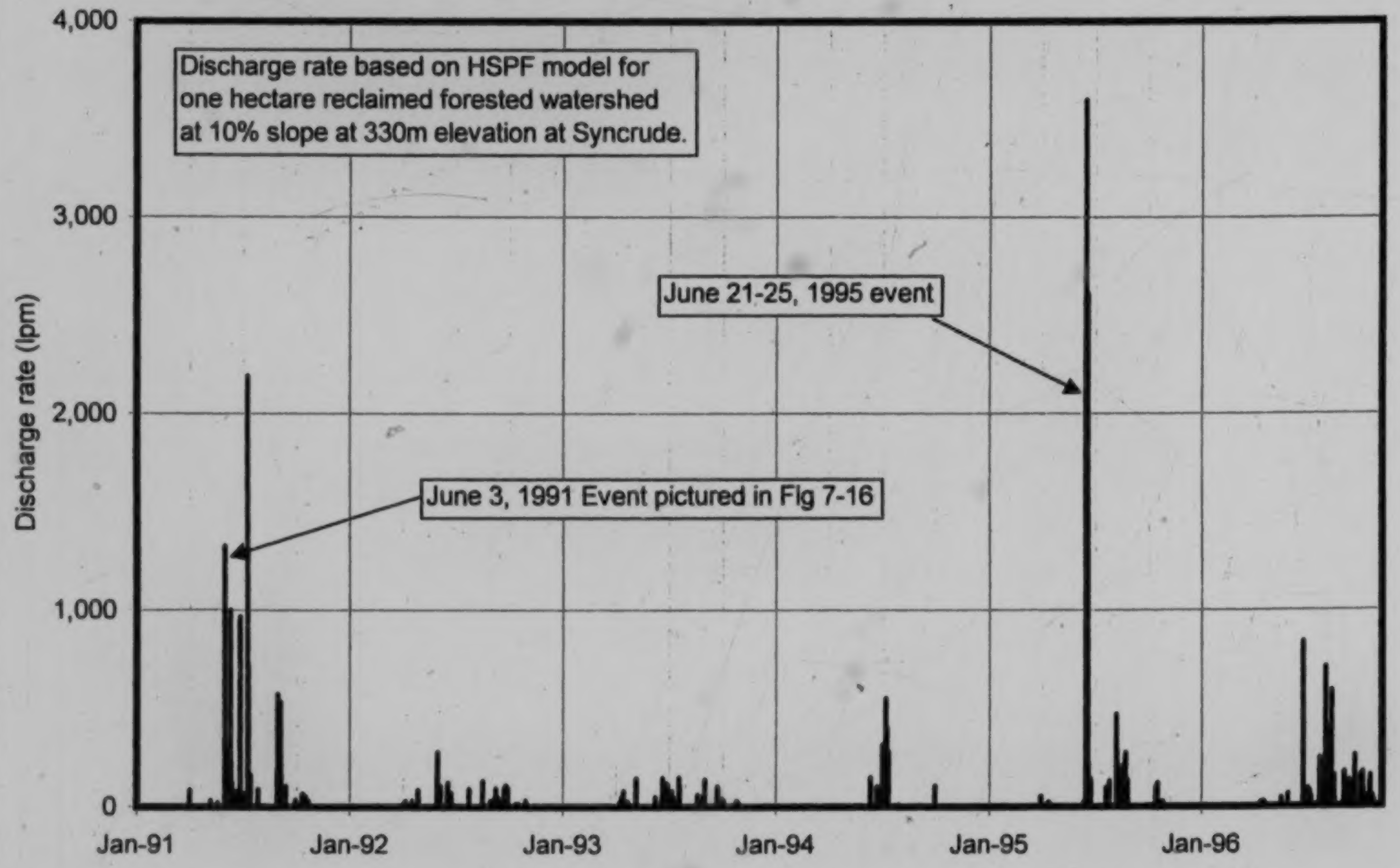
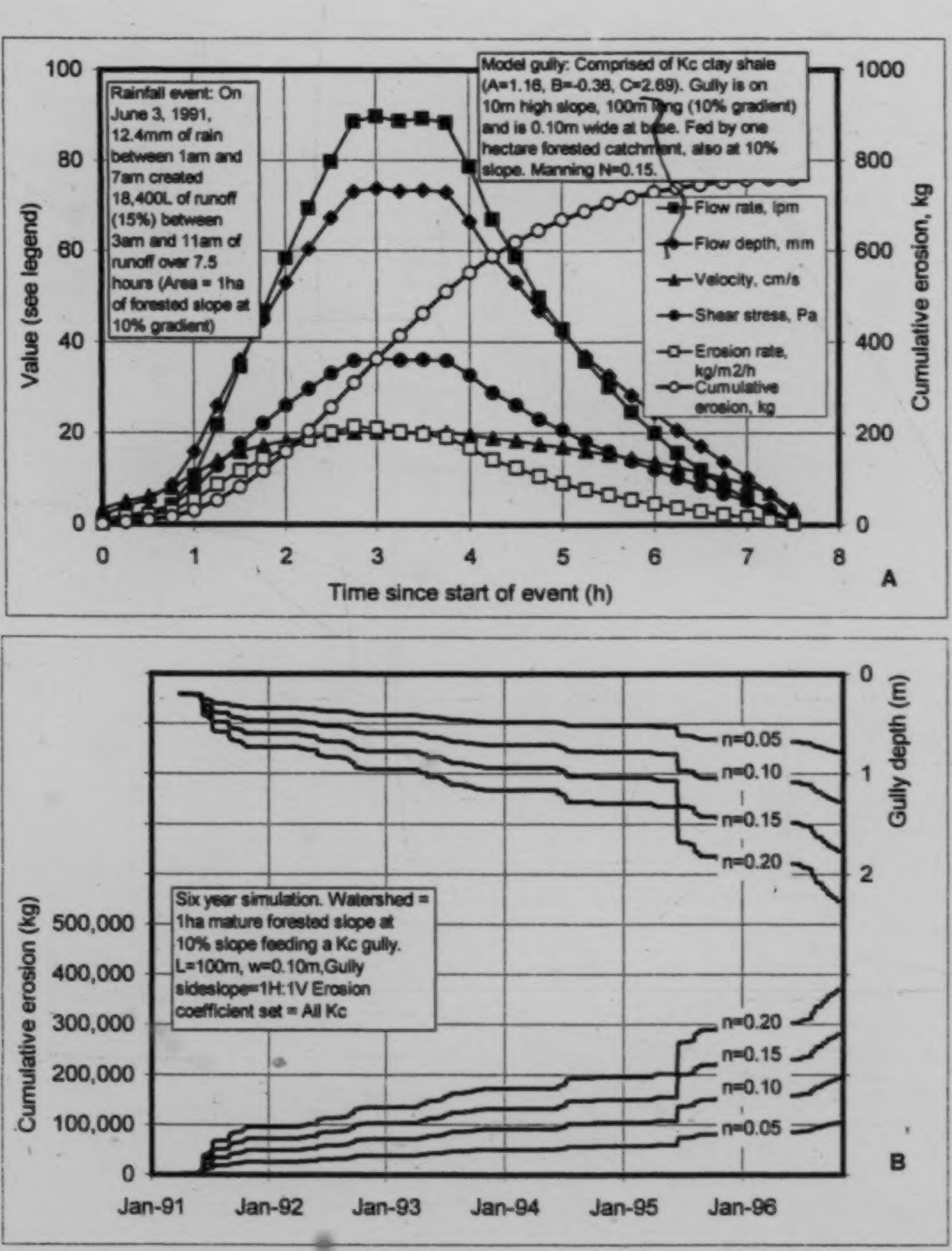


Figure 7-16 Modelled gully erosion due to a single rainfall event and cumulative erosion over six years.



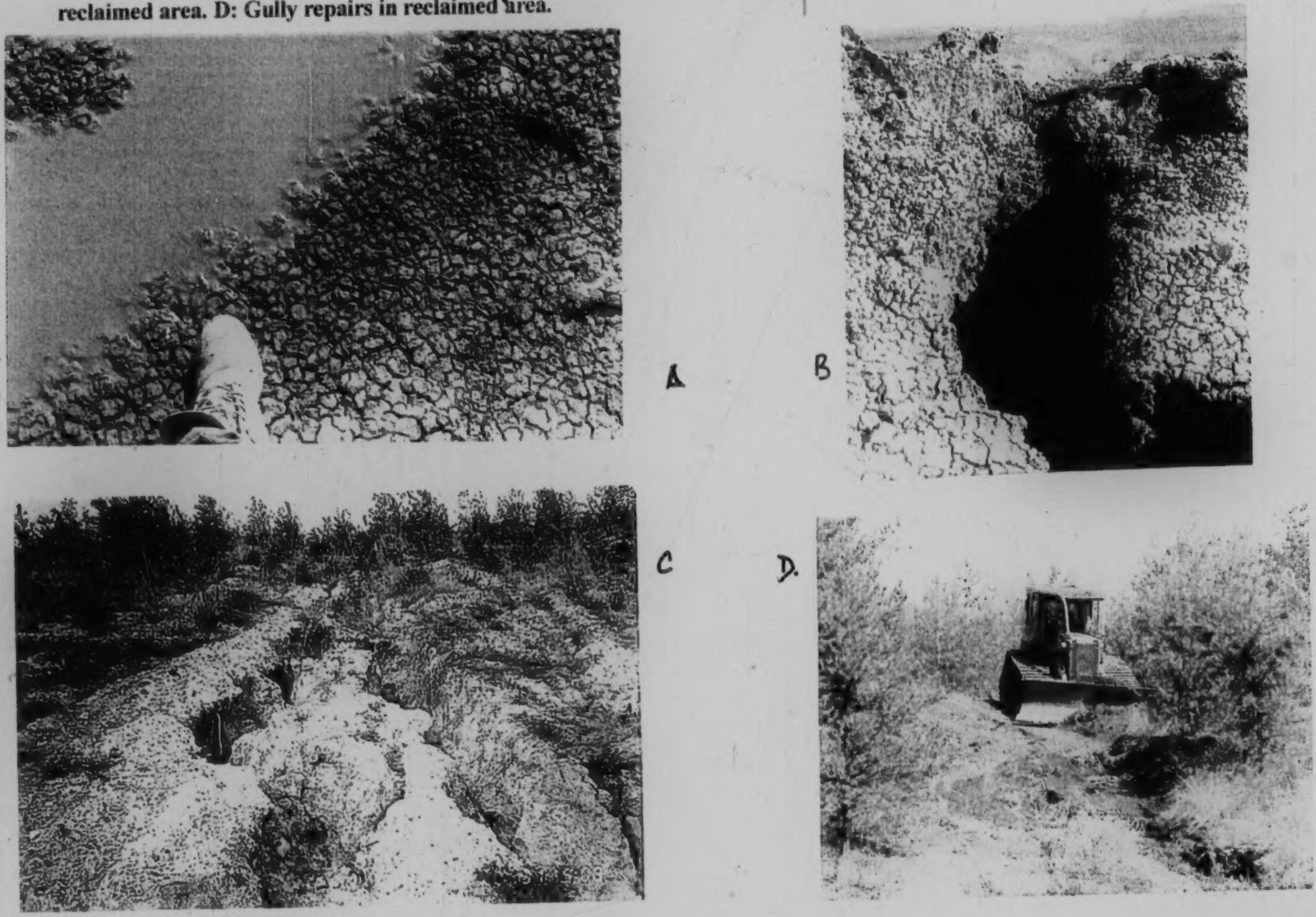
Rainfall event: On June 3, 1991, 12.4mm of rain between 1am and 7am created 18,400L of runoff (15%) between 3am and 11am of runoff over 7.5 hours (Area = 1ha of forested slope at 10% gradient)

Model gully: Comprised of Kc clay shale (A=1.16, B=-0.36, C=2.69). Gully is on 10m high slope, 100m long (10% gradient) and is 0.10m wide at base. Fed by one hectare forested catchment, also at 10% slope. Manning N=0.15.

Six year simulation. Watershed = 1ha mature forested slope at 10% slope feeding a Kc gully. L=100m, w=0.10m,Gully sideslope=1H:1V Erosion coefficient set = All Kc

Value (see legend)
0
20
40
60
80
100
Cumulative erosion, kg
0
200
400
600
800
1000
Time since start of event (h)
0
1
2
3
4
5
6
7
8
Flow rate, lpm
Flow depth, mm
Velocity, cm/s
Shear stress, Pa
Erosion rate, kg/m2/h
Cumulative erosion, kg
A
Gully depth (m)
0
1
2
Cumulative erosion (kg)
0
100,000
200,000
300,000
400,000
500,000
n=0.05
n=0.10
n=0.15
n=0.20
n=0.20
n=0.15
n=0.10
n=0.05
Jan-91
Jan-92
Jan-93
Jan-94
Jan-95
Jan-96
B

Figure 7-17 Gully erosion on constructed landforms. A: Shallow ponded water and the effect on Kc fill. B: 1m deep gully on Kc slope before regrading. C: Active gully erosion in a reclaimed area. D: Gully repairs in reclaimed area.



Chapter 8

Conclusions

This thesis highlights the need for a formal approach such as landscape engineering as a new framework for creating reclaimed landscapes. Chapters 2 and 3 identified the state of practice in closure planning and landscape design and summarized the state of reclaimed landscape performance, highlighting the gap between expectations and deliverables. Chapter 4 introduced the ideal of "successful reclamation." Chapter 5 introduced the new discipline of landscape engineering, meant to provide a more reliable framework for setting and meeting goals through a more engineering approach, with particular emphasis of goal setting, planning, and design. Chapters 6 and 7 illustrated approaches within landscape engineering to estimate and design for fluxes – in the first case, a water balance in tailings sand, in the second, rates of erosion (and hence of landform evolution) in a mining landform constructed of dispersive clay fill.

8.1 Conclusions organized by chapter

State of closure planning and experience

- Closure planning, though still in its infancy, is becoming common. Largely driven by legislation, the approach is providing dividends for mines in identifying liabilities, and guiding long term planning. However, closure planning is usually poorly integrated with other mine planning and mine operations, except in the case where mines are already in the post-closure period and some new mines..

- The goal setting process is of particular concern. Goals are poorly defined, often complex, and usually unachievable. Reclamation goals often exceed those of regulators, but are seldom realized.
- There is a certification trap and a liability trap. Almost no mines have applied for government certification of reclaimed land and are unwilling to return control over to the government while still liable for landscape performance. At closure, reclamation activities often slow dramatically, and the land is often being held in long term dormancy. The mining industry is not presently following its social covenant of "temporary use of the land."

State of landscape design and performance

- Landscape design is still in the artisan stage. Rules of thumb or simplified descriptive approaches are used. Often the work is field fitted without prior design.
- The approach has been moderately successful for most terrain units, however areas of tailings sand slopes, soft tailings, and surface water hydrology (particularly creeks and end pit lakes) are wanting. Geotechnical and revegetation disciplines are among the most advanced and most successful.
- Most sites will require at least some low level of long term, perhaps declining maintenance to meet even modest landscape goals. The ability to walk away from reclaimed sites should be considered the exception rather than the rule. Some sites will require intensive (daily) monitoring and maintenance in perpetuity.
- A more integrated approach is required – combining the skills of various disciplines through the life of each mining landform. Most of the design and construction techniques needed are being practised at one or more of the mines visited, so the required change is more procedural than technological.

Successful reclamation

- Successful reclamation has been defined as that which supports the mining company's operational and corporate objectives, allows reclamation certification and transfer of liability, and can be reasonably assured of providing acceptable long term performance.
- Elements of successful reclamation go beyond closure planning, design, and construction to include management support, stakeholder involvement, communication, economics and

decision making, research and development, landscape performance, risk management, and independent audit.

- For each category there is at least one mine that scores highly, but for the most part, mines score in the low to medium range. Successful reclamation is not presently being achieved.
- To achieve successful reclamation, four changes are needed:
    - mines need to embrace all aspects of successful reclamation and integrate this program operationally
    - a framework of landscape engineering (or equivalent) needs to be implemented at each mine
    - mines (and regulators) need to focus on progressive reclamation and progressive closure
    - legislators need to amend laws to allow for full transfer of liability for well-reclaimed sites.

Landscape engineering

- Landscape engineering is introduced as a specialized branch of engineering aimed primarily at mine reclamation at the landscape scale. It is a composite of the many biological and physical sciences and engineering disciplines presently involved in reclamation but operating under a common framework.
- The goal of landscape engineering is the creation of reclaimed landscapes that meet the goals of mining companies (and their regulators) during mine operation and those of society and the new custodian after mining.
- While it encompasses all elements of traditional engineering, landscape engineering is focussed on three main areas: the ongoing cycle of closure planning, landscape design, and landscape performance assessment.
- Technologies that unify landscape engineering include use of flux modes and risk management techniques for landscape design, construction and operation.
- Following the progression of other engineering specialties, landscape evolution is the natural and perhaps inevitable evolution of mine reclamation from the artisan stage through to a recognized discipline. Full adoption, however, is likely to spread slowly over the next several decades.

Geostatistics of tailings sand permeability

- The use of simple geostatistical tools for the design engineer are described and demonstrated using a very large database of oil sands tailings sand permeability. Descriptive statistics, upscaling, autocorrelation, and probabilistic approaches are described and demonstrated. These simple but powerful tools are rarely applied to geotechnical applications, even at the research level, but in some cases, the state of practice compensates through rule of thumb or other implicit processes. The effects of scale are particularly important to the landscape engineer.
- Two of the main variables that affect groundwater fluxes and water table locations in reclaimed land are the rate of percolation (groundwater recharge) and substrate permeability. Unfortunately, these can often only be estimates to within a factor of two to five.
- Landscape designs need to accommodate this high level of uncertainty through the use of probabilistic analysis, conservative design, agreement to only modest goals for future performance, and the use of pilots and prototypes to refine field parameters and performance, and in some cases relying on the observational approach to make timely and economical changes in the future should performance warrant.

Accommodating erosion of constructed dispersive clay landforms

- Erosion of landforms remains an impediment to successful reclamation, often due to unreasonable expectations of regulators.
- A survey of erosion predictions is provided that focuses on the levels of uncertainty inherent in monitoring and modelling. While there are many models for predicting erosion, most are only accurate to within +/- 50 percent under highly controlled conditions and for specific runoff events. Overall, well-calibrated models are only accurate to within one half to one order of magnitude. Gully erosion, in particular, remains the hardest to predict.
- Faced with these high levels of uncertainty, the landscape engineer still needs to design and construct landforms that have a reasonable assurance of meeting agreed upon landscape performance goals. To achieve this, the designer needs to use available methods to predict erosion. Goals need to be modest and clearly defined, and landforms designed to accommodate the inevitable erosion.

- A simple laboratory flume procedure was developed and tested against field performance for a dispersive clay fill. There was a modest agreement between laboratory and field methods, but field flumes showed much higher Manning roughness coefficients.
- Strategies for landform design to accommodate erosion include landform grading – especially creating a series of sub-hectare catchments on slopes, avoiding ponding water on slopes and plateaus, and designing depositional areas to handle depositional fans without compromising overall landform performance. Monitoring and maintenance for the first few decades after construction may be required.

8.2 Overall conclusions

Mine reclamation is a nearly universal activity at active mines. Closure planning, while still in its infancy, is widely practised. The design and construction of mining landforms is in its artisan stage, and while producing dramatic results, is ultimately failing to meet the mines' and regulators' needs. Successful reclamation eludes nearly every mine – the amount of land being turned back to the state is nearly zero. While this is partly due to poor performance of some terrain units and in some discipline areas, it is generally due to a lack of willingness to accept liability when future landscape performance is uncertain.

Landscape engineering is offered as a potential solution to this dilemma. It embraces uncertainty as part of its design process, and focuses on planning and design to meet reasonable goals with reasonable assurance. It builds on the wealth of existing success and knowledge and know-how of the various disciplines presently involved in mine reclamation and provides a framework and robust engineering tools. Perhaps its use will improve the view of mine reclamation practice, helping to allow for greater liberalisation of liability transfer laws, to the point where mining can better claim to be a "temporary use of the land."

8.3 Summary of contributions

This section provides a summary of the contributions made by this study:

- Description of the current state of practice in mine reclamation, landscape design, closure planning, and mine closure through visits to 69 mines

- Development of a framework for assessing landscape performance – by discipline and by anthropogenic terrain units
- Identification that there is poor success rates for some disciplines and some terrain units (especially hydrology and tailings areas)
- Highlighting that the present state of practice does not yield successful reclamation, that despite large expenditures and good intentions, mining is not fulfilling its social contract of being a "temporary use of the land" and that the viability of the mining industry is threatened
- Compilation of reclamation and closure goals, challenges, and novel concepts
- Defining the notion of successful reclamation and its elements, including a scorecard and scoring of present practice
- Development of the new discipline of landscape engineering
- Description and framework of typical engineering activities and stages of engineering development
- Development of a large database of permeability values at a variety of scales and with a variety of test methods. Interrogation of the database for scale effects, coefficient of variation, upscaling, and autocorrelation
- Demonstration of the coefficient of variation of permeability (log permeability) as a geotechnical parameter
- Confirmation of various empirical rules of thumb with simple geostatistical analysis and demonstration of simple geostatistical tools.
- Creation of an risk-based framework to the shrewd-farmer drainage spacing problem
- Creation of a laboratory erosion technique for dispersive clay gully erosion
- Identification of the large variability common in erosion rate predictions (order of magnitude uncertainty), the folly of specific erosion rate regulations, and alternative methods of dealing with uncertainty in erosion during landform and landscape design and through long term declining maintenance.
- Identification that there are inherent limitations to predicting long term landscape performance, and that much of the focus should be directed through accommodating this uncertainty through agreement only to modest goals, thoughtful design practices, and other institutional mechanisms.

8.4 Areas of potential future research

The section provides a summary of potential areas that would benefit for additional research.

- Planned visited to a large number of mines with a checklist of questions provides a useful method to determine the current state of practice and to observe landscape performance. Such a program, run approximately every ten years, would allow tracking of changes at specific sites, and within the industry.
- In that landscape engineering would most benefit from the systematic application of available technology, the next steps are less research focused, and one of communication and persuasion, largely through demonstration and word-of-mouth contact.
- Landscape engineering is not a spectator sport – it requires rolling up one's sleeves and tackling real issues at real mines. So one of the areas of advancement needed is promotion of landscape engineering, and observing how it evolves where practised. If it becomes adopted at a few mines or consulting firms, a conference style workshop to compare notes and share advances would be worthwhile.
- The work on dispersive clay erosion would benefit from a larger scale field erosion test and ongoing monitoring of reclaimed dispersive clay landforms, with special attention on a forensic investigation and back analysis when the next large gully is formed.
- Given the inherent uncertainties in erosion modelling, it would be interesting to ask the model developers to concentrate less on promotion and more on practical use of the models with a focus on better understanding the inherent uncertainty. An international symposium on accuracy in erosion modelling would produce interesting results, particularly if attended by developers.
- In the area of predicting water tables and fluxes in reclaimed landscapes, software is starting to become commercially available that would allow examination of the effects of spatial variability on landscape performance using three-dimensional groundwater modelling combined with stochastically populated cells to simulate field variability. It would be useful to compare and rationalize differences between leaching rates of solutes at lab versus field scales. Additionally, work to better understand the sources of error for common permeability measurement techniques would be useful.
- Perhaps the area with the greatest potential is to foster publication of landscape engineering case histories, as a method to develop, enhance, and promote basic techniques, and get a

better understanding of its application, limitations, and the level of effort required. This process has proved valuable in environmental geotechnique and ecological engineering over the past decade. A successful journal devoted to landscape engineering would be a welcome addition.

University of Alberta

Sustainable mine reclamation and landscape engineering

by

Gordon Thomas McKenna

A thesis submitted to the Faculty of Graduate Studies and Research in partial fulfilment
of the requirements for the degree of Doctor of Philosophy

in

Geotechnical Engineering

Department of Civil and Environmental Engineering
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Fall 2002

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Appendices

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Appendix A

Closure planning, landscape design, and landscape performance at 69 mines

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A NOTE TO READERS

This appendix contains many controversial elements. While the author is willing to defend the conclusions reached, the information, conclusions, and philosophy provided here are the author's and not necessarily those of any other person, institution, or company. In fact, given the number of viewpoints, complexity, and rapid evolution of this area, there is likely no one who will agree with everything stated in this appendix. Hopefully, the major themes and findings strike a chord with most readers.

Furthermore, most of the information in this appendix comes from driving tours with reclamation specialists at each mine, as we bumped along winding mine roads. It is unlikely that all of the information was heard and recorded with complete accuracy. As well, much of the information is time sensitive – mines are reclaiming large tracts of land each year and the practices are evolving rapidly. So, while the overall observations and general conclusions are thought to be sound, the reader is warned against using details gathered at the individual mines. It is recommended the reader focus on the big picture results.

A long list of supplements is presented at the end of the appendix including a series of lessons learned over the past eight years.

ACKNOWLEDGEMENTS

This work has benefitted from the contributions and advice of over 100 people and is a compilation and organization of their input.

The following individuals are thanked for their time and openness in providing tours of their sites: Alex Jakubick, Bill Mitsch, Brent Hartley, Cam Bateman, Don Sheeran, George Hopkins, Glen Hall, Gord Livingstone, Horst Schor, Ian Horne, Jim Lant, Laurie Healey, Marty Puro, McCoy, Mike Aziz, Nan Davé, Richard Dawson, Roger Berdusco, Ron Jones, Ross McArthur, Sam Cho, Steve Janesewski, and Steve Tuttle.

The following companies are thanked for providing access to their sites and sharing their information: BHP Minerals, Falconbridge, Fording Coal, WISMUT, Highland Valley Copper, Atlas Historic Society, Imperial Metals, INCO, Lee Ranch, Luscar, Manalta Coal, MK Reclamation Co., Navajo Nation, Noranda, Ohio State University, Laguna Construction Company, Pittsburgh & Midway Coal Mining Company, Placer Dome, Rio Algom, Seven Industries, SF Phosphate, Shell, State of Utah AML, Suncor Oil Sands, Syncrude Canada, Taseko Mines, Three Sisters Resorts, Transalta Utilities, and Westmin Resources.

The following people are thanked for their input into the study: Andy Robertson, Dave Devenny, Dave Sego, Frank Munshower, John Errington, John Gadsby, Les Sawatsky, Nordie

Morgenstern, Richard Dawson, Scott Fisher, Terry Macyk, Tim Eaton, and the Syncrude Land Restoration Technical Advisory Panel.

Syncrude is thanked for its support of this work. In particular, Bob Shaw, Howard Ellis, John Oxenford, Paula MacGillivray, Ted Lord, and Wayne McKee are thanked for their support. My landscape and reclamation colleagues at Syncrude, who have worked these issues and participated in many discussions and debates, have helped to form these conclusions. These colleagues include Beat List, Bob Cameron, Brad Strueby, Clara Qualizza, Dan Lovbakke, Earl Anderson, Graham Cuddy, Janelle Ducharme, Jonathan Matthews, Marie Keys, Rick Lahaie, and Terry van Meer.

In particular, Richard Dawson is thanked for accompanying me to many of the sites, sharing his thoughts on these subjects during late-night meals in small towns on the road between mine visits, and helping to organize the findings when we returned to the office. Dianne Trach is thanked for her help in preparing this appendix – and the dozen presentations and updates in between – and helping to craft the message and communicate it effectively. And most especially, thanks goes to my lovely wife Yvonne, who kindly persevered at home alone with our two young sons as I travelled to exotic destinations across the country, and who allowed me time on our family vacations to visit mines by the side of the road.

Plate i **Three intrepid explorers at the Atlas Historic Mine near Drumheller in 1998. Featured are Richard Dawson (right), Horst Schor (centre) and Gord McKenna (right).**

1.0 SUMMARY

1.1 Program summary

To determine the state of practice in closure planning and landscape design, a program was undertaken to visit 69 mines in Canada and the United States. The mines visited varied in age, size, commodity, mining method, climate and regulatory regime. The goals of the program were to determine the state of closure planning and landscape design and to observe the performance of reclaimed landscapes.

Most operating and recently closed mines use closure planning as an effective tool in mine and reclamation planning. However, most have only started using closure planning in the past five to ten years, spurred on by regulatory requirements. The production and use of these plans is still on the steep portion of the learning curve and advances over the course of the five-year study were noted.

Setting goals for reclamation and long-term landscape performance is an area for improvement. Though goals exist, most are vague and many are unrealistic. Mines need to set a few key, clear goals, and work hard to achieve them.

Most reclaimed landscapes receive little design attention other than geotechnical. The reclamation specialist is usually left to reslope and green up whatever the miners leave behind. Surface-water hydrology is usually completely overlooked and, in most other cases, poorly handled. Revegetation is one area that is particularly advanced and well handled but, as a result, receives more regulatory constraints such as restriction to native plants.

Most medium and large-sized mines will require some form of long-term monitoring and maintenance to continue to meet their landscape performance goals. The need is usually not recognized until closure looms. Understanding and acceptance of long-term maintenance varies from province to province.

Despite a near lack of formal design, most reclaimed landscapes are performing well. The sites are generally free of physical hazards (such as buildings, debris, and open shafts); have been regraded and topsoiled; and are growing lush vegetation, most commonly agronomic grasses. Mines are reclaiming progressively but, because most areas of the minesites remain active throughout the life of each mine, typically only 10 percent of the landscape is reclaimed prior to closure.

Despite the good overall landscape performance, significant improvements in the state of practice are needed. On the design side, groundwater hydrology, soils and, especially, surface water hydrology need more attention. In terms of landscape units, creeks, areas of soft tailings and slope designs need improvement. In particular, two types of landscape units stand out: tailings slopes are almost universally performing poorly and the filling rates and final elevations of lakes in mined-out pits are seldom accurately enough predicted.

Though many would argue that mine reclamation is well in hand, it is presently unsuccessful at achieving its major goals – reducing liability and return of the land to the original owner (usually the Crown). Only one or two mines visited had land that had been certified as reclaimed or returned to the owner. Mines are generally unwilling to return the land and the Crown is unwilling to accept it. Today, mining is still a one-time rather than temporary use of the land.

The reason for the barrier is that it is difficult, if not impossible, to assure that the reclaimed minesite will meet and continue to meet the goals and regulations. The landscape system is too complex, the goals are poorly defined, and influences on this system (extreme or perpetual forces, human interference, and regulatory change) are too great. Few are prepared to accept the long-term liability for sites under these conditions.

To attempt to resolve these issues of planning, design, performance, and liability, the concept of landscape engineering is developed. With an attempt to bring forth a more holistic approach, landscape engineering focuses on goal setting, closure planning, integrated multidisciplinary landscape design, performance assessment and liability ownership / transfer.

For mining to fulfil its promise as temporary use of the land, it must ensure better design and construction of landscapes, recognize the inherent uncertainty in landscape performance, and work on methods of signoff and liability transfer based on demonstrated due diligence and transparency.

1.2 Summary of findings

In the broadest of terms, the findings can be summarized as follows:

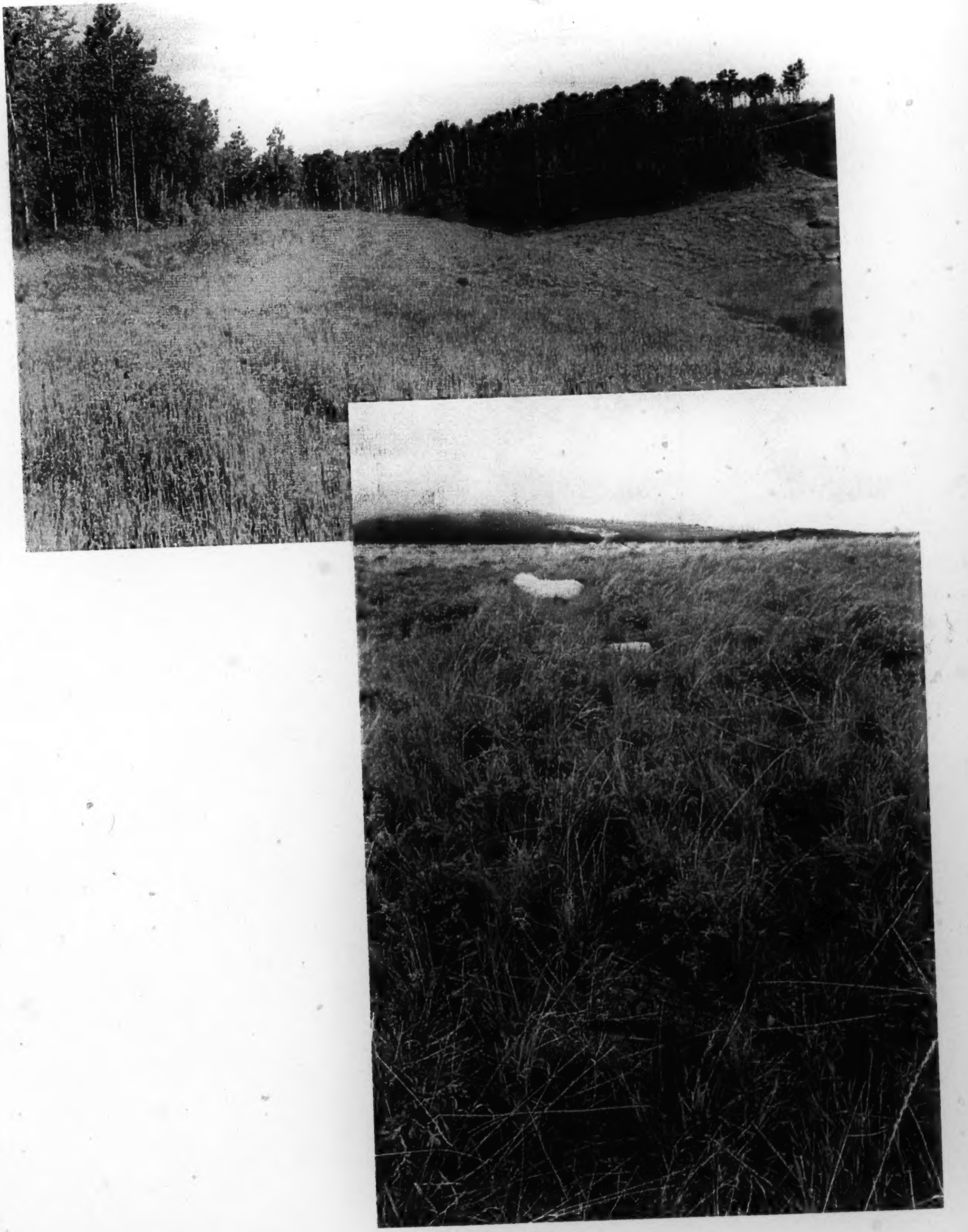
- Most mines are in the early stages of closure planning and the outcomes of this process are being used by the mines and regulators to plan and schedule their landscape and research activities. Goal setting remains a problem.
- Most landscape performance is good and is likely to meet modest but reasonable landscape performance targets. Surface water hydrology and tailings sand slopes remain problematic.
- In terms of successful reclamation, most mines are good at the “hard issues” of technical know-how, but poor at the “softer issues” like public involvement, financial management, and independent review.
- Despite good intentions and large sums of money spent on reclamation, mines are failing at their overall objectives of reducing liability and returning the land. As well, the whole notion of temporary use of the land is not being achieved. As a result, a certification barrier, a custodial transfer barrier, and a liability trap exist that need to be addressed with a new framework.
- Our knowledge about landscape performance, reclamation methods and long-term maintenance has highlighted deficiencies in the current framework of design and regulation. Changes are needed to reflect the new level of understanding.

On a more basic level, the following learnings came to light through the visits to the 69 mines:

- Every mine has a unique contribution to the reclamation industry. They should be encouraged to promote themselves and share more information, performance data, and successes with the industry. More joint industry, government, and stakeholder forums (for example, the annual British Columbia Mine Reclamation Symposium) need to be created and fully supported.
- Almost every mine overlooks, under-rates, or ignores some key aspect of long-term performance. There is a focus on what can be done and an ignorance of key unzippering mechanisms.
- Mines are asking too much and too many things from their closure landscape. There are often too many and conflicting end land uses, productivity requirements are onerous, stability is over-specified, and aesthetics are creeping in. Mines try to do everything for everyone, especially for themselves and, instead, should focus on becoming experts on a few key parameters.
- Sometime within the next few decades there will be a rationalization of mine reclamation, its regulation, and liability that will resolve many of the outstanding issues. Before that, times will become critical, and industry and governments will work together on a new framework. In the meantime, conditions will continue to get more difficult. To aid the upcoming transitions, mines need to show due diligence and good environmental performance, especially in the areas of goal stetting and permitting, closure planning, and landscape design, construction, reclamation, and maintenance, to help pave the way to change.

From the work presented in this appendix, the new discipline of "landscape engineering" is emerging to more formally and systematically address the planning, investigation, design, construction, monitoring and maintenance of these new landscapes.

Plate 1.0 Examples of typical good reclamation of mine dumps in British Columbia



2.0 INTRODUCTION

2.1 Background

The mining industry is presently undergoing a revolution in the way that it carries out its long-range planning and development. The main change is the use of closure planning which involves effectively planning for the landscape that will exist when a mine is complete and operations have finished. Mining companies and regulatory agencies worldwide are beginning to recognize the importance and value of closure planning.

Some mines are also recognising the importance of achieving acceptable landscape performance. While challenging enough, just meeting planning and reclamation regulations is not sufficient – what is really required by the regulators, stakeholders and mine owners is acceptable performance of the reclaimed landscape. There has been little work on setting reasonable goals and establishing methods to reliably achieve those goals, and no systematic review of the landscape performance of reclaimed mines.

The planning and reclamation activities reflect recent events in the mining industry. The mining industry is North America is in decline and many mines have closed in the past ten years. Much of the production has moved to third-world countries where permitting is faster, costs are lower, and in some cases, ore grades and orebody sizes presently being exploited are greater.

The 1990s saw a strong push towards stricter environmental policies in North America (and generally worldwide) and part of this has been the advent of closure plans being required by many jurisdictions.

Mines today are mostly operating at very low profit margins, and those are only a result of rapidly advancing technology – especially larger mining equipment.

The combination of the closure of many large mines, increased expectations for the reclaimed minesites, and miners and shareholders becoming more sophisticated, has resulted in reclamation and closure planning being better recognized as an important aspect of mining. Sophisticated individuals at the mines recognize that mine reclamation practices and regulations lag behind the technical understanding and stakeholder expectations and they are actively experimenting with improvements to their practice. A rapid evolution, even a revolution in mine closure planning and reclamation design is underway.

2.2 Study purpose

The purpose of the program was to gain a better understanding of the state of practice in closure planning through visits to a variety of mines and to assess first-hand how the reclaimed landscapes are generally performing. To accomplish this, the author visited a total of 69 minesites located in Canada and the United States.

2.3 Methodology

In preparation for the mine visits, a list of potential candidate sites was prepared through discussions with the author's thesis supervisors, mine closure consultants, Syncrude staff, and mine regulators. Table 2.1 provides a list of the sites and their locations. Generally, sites were chosen based on three criteria:

- sites that were nearing closure
- sites available to visit on conference tours
- other sites available during the author's normal business and vacation travel.

Clearly, the sites do not provide a statistical sampling of mining or reclamation activities. However, they do provide a wide breadth of locations, mining methods, ores, regulatory jurisdictions, geology, climate, and mining dates, and size of disturbance. The large number and diversity of sites is thought to provide a reasonable database upon which to draw conclusions about the state of closure planning practice and the performance of reclaimed landscapes.

The data collected is somewhat time-sensitive. Even over the four-year study, closure planning had become more prevalent. Indeed, Mount Polly Mine, visited in 2000, was one of the first mines to open with a closure plan in place. So the work essentially captures the state of practice in the late 1990s with respect to closure planning and reclamation and typical reclaimed landscape performance. Visits to older and abandoned mines helps to document some of the practices of the past, and the performance of older landscapes as well.

To gather information, the author took mine tours at the different sites. The author visited 66 of the 69 sites and the other three were visited by colleagues from Syncrude. As well, Richard Dawson of Norwest Mine Services visited many of the sites with the author and helped with many insights and observations.

Mine tours lasted several hours and involved visiting most areas of each minesite. A checklist (see Table 2.2) was used to make observations, ask questions on the tour, and organize information after the tours. Over 4,000 photographs were taken in an effort to detail landforms and landscape performance. Additional information was obtained through reports and handouts from the mines, government maps, company and government Internet web sites. Trip reports summarized the results.[1]

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[1] The following is a list of reports that cover the mine visits (these and other references are listed in the Reference section at the end of the body of this report):

- Keys, M-J., 1996. Mine closure and reclamation practices at three central Alberta coalmines, Syncrude Canada Ltd, Fort McMurray.

About 75 percent of the sites had a guide from the mining company who answered the long list of questions as the site was toured. Almost everyone was frank and open and provided lots of advice and suggestions.

Caution should be noted in the specifics of the data gathered. Most of the information was provided by the local reclamation specialist while driving around the sites on rough mine roads, and different levels of data were provided or gathered at different sites. Some of the information may be misinterpreted and key elements may be missing. In some cases, for example in determining values of disturbed areas and latitudes and longitudes, data was estimated using topographic maps and from photographs. And, some of the data – for example, amount of reclaimed areas, main goals and ownership status – is very time sensitive. So while the general conclusions and trends are useful, the reader is cautioned against relying on the specific details collected at each minesite.

2.4 Overview of mines visited

A wide variety of mines in a large number of geographic regions were visited during the study. By visiting a large, diverse sample of minesites, and systematically recording key observations, a database was created that can be relied upon to reasonably characterize the state of practice of closure planning and the performance of reclaimed landscapes. Figures 2.1 through 2.14 were prepared by querying this database compiled from the mine visits.

Figures 2.1 and 2.2 provide background information about the mines visited. The graphs provide a sense of the types, sizes and locations of the mines visited. They also show that a wide range of mines were visited from small to large, from old to new, and mining a range of commodities in a variety of climatic regions.

- McKenna, G., 1996. Active maintenance and other post-closure practices at three northern BC metal mines. Syncrude Research Department Progress Report, 25(7).
- McKenna, G., 1996. Reclamation and mine closure practices at fifteen minesites in the arid American southwest. Syncrude Research Department Progress Report, 25(3): 126-215.
- McKenna, G.T., 1996. Mine closure practices at three BC Southern Interior Metal Mines. Research Department Progress Report, 25(6): 77-124.
- McKenna, G., 1996. Mine closure practices at two Vancouver Island metal mines. Syncrude Research Department Progress Report, 25(5): 18-51.
- McKenna, G.T., 1999. Highway reconnaissance of some Central Alberta landforms and slopes, Syncrude Canada Ltd, Fort McMurray.
- McKenna, G.T., 2000. Closure planning practices and landscape performance at two metal mines near Williams Lake, B.C. Syncrude Canada Ltd, Fort McMurray.
- McKenna, G.T., 2000. Mine closure planning practices and landscape performance at nine minesites in Sudbury and Elliot Lake, Ontario. Syncrude Canada Ltd, Fort McMurray.
- McKenna, G.T., 2000. Landscape engineering at Buckeye Swamp, Ohio State University, Syncrude Canada Ltd, Fort McMurray.
- McKenna, G.T., 2000. Mine closure practices and landform performance at Rocky Mountain coal mines and other mining sites, Syncrude Canada Ltd, Fort McMurray.

Figure 2.1 is a map illustrating the mines visited and shows a general grouping of the mines. The mines are mostly clustered in Western Canada and the Colorado Plateau, with a few in Ontario and one in Ohio. Figure 2.2 shows the number of mines visited in each region.

Figure 2.3 shows the wide range of amounts of precipitation experienced by mines. In this survey, annual precipitation ranged over an order of magnitude from 160 millimetres at the semi-arid Colorado Plateau to 2000 millimetres on Vancouver Island rainforest. Variations from year to year and the intensity of rainstorms also vary. Climate is one of the major factors in landscape design and performance, and any encompassing system needs to recognize the variations between mines and from year to year. Few mines consider climate in their reclamation work other than in choosing vegetation.

Figure 2.4 shows the major mining methods employed at the mines visited. Most were open-pit mines and many were underground. Underground mines generally have a much smaller footprint, but not necessarily fewer closure planning concerns than open-pit mines. A few sites use both underground and open-pit methods. Landscape design methods need to be cognizant of the many different forms that mining takes.

Figures 2.5 through 2.7 show the opening and closing dates for the mines. It is interesting to note that the mine opening dates are roughly evenly distributed over the last 100 years but many were closing in the 1990s. The 1990s closures[2] are partly due to selection of these mines for visiting (to learn about closure first-hand) but also perhaps due to low commodity prices and movement of metal production to other countries. Figure 2.7 shows the typical lifespans of mines. While some of the oldest mines are entering their second century of operation, most mines have a life of about 25 years, which is probably mostly influenced by mining economics and typical equipment lifespans.

The result of these closure dates is that most miners will experience at least one final mine closure during their working careers. Closure planning, an activity that generally only started in the last 10 years, as well as landscape engineering (a discipline just starting now) will mostly be retrofitted to mines that started without closure planning and landscape design, and to some mines operating mines and mining regions that are a hundred years or older. Clearly, these activities, along with new regulations and new regulatory framework need to be designed to handle both new and old mines.

Figures 2.8 and 2.9 show the wide range in mining rates, spanning five orders of magnitude from 10 tonnes per day to one million tonnes per day (ore plus overburden/waste). Medium-sized mines often range in the order of 10,000 to 30,000 tonnes per day, and large mines in the 100,000 to 200,000 tonnes per day.

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[2] According to data provided by Morrison 2001, between 1994 and 1999 in Canada there averaged eight new mine openings, eight suspensions, eight reopenings, and eight closures (in 1999 there were 277 operating mines in Canada). Most of the closures occurred in the latter three years.

Rather surprising in retrospect, the sample of Canadian mines represents a significant fraction of Canadian ore production. In terms of annual ore production, the total production of Canadian open pit mines visited was 100 million tonnes per year, or about half of the Canadian open-pit mine production[3]. In terms of underground mines, production of the mines visited was about 18 million tonnes per year[4] or about one third of Canadian production. Open pit oil sands production of 292 million tonnes per year was 100 percent of mined oil sand production[5]. Since only a small fraction of Canadian mines were visited[6], clearly the sample must have been skewed to the larger producers. In contrast, the ratio of production at visited to total U.S. mines is minuscule.

Larger mines usually have greater cashflows than smaller ones and have greater resources to deal with reclamation, closure and research into each of these activities. They often have greater incentives to do a good job and to minimize their unit costs. Reclamation research is more prevalent at larger mines.

Figures 2.10 and 2.11 show the range of disturbed and reclaimed areas. Again these have a wide range, from one hectare to 15,000 hectares. Not surprisingly, underground operations tend to have small disturbances, typically 10 to 100 hectares. Open-pit mines tend to range from 500 to 5,000 hectares. Large coal and oil sands mines have the greatest disturbance. A recurring theme was an open-pit metal mine with a waste rock dump and a tailings pond each equal in area to the mined-out pit and totalling about 500 to 1000 hectares.

The Canadian mines visited represent about 40 000 hectares of disturbed area, about 10% of that disturbed by Canadian mines.[7]

Areas that are greater than about 100 hectares are relatively complex to reclaim. They are not just a component of the surrounding landscape but landscapes in their own right with various landforms and watersheds, and usually a variety of goals and land uses. They also often attract more stakeholder and regulatory attention than small sites.

Figures 2.10 and 2.11 also indicate that most operating mines have about 10 percent of their area reclaimed, even in this era of progressive reclamation. This low level of reclamation is due to the fact that many of the tailings ponds and dumps are active throughout the mine, and not available for reclamation until near closure. (An obvious exception would be coal strip mines that have only a small area of open mining area, and reclaim about as much as is disturbed each year.)

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[3] Based on average 1995-1997 ore production statistics featured in Natural Resources Canada, 1999. Mineral and metal commodity review 1999. Natural Resources Canada, Government of Canada.

[4] Influenced in particular by visits to the Inco and Falconbridge smelters in Sudbury which receive ore from dozens of underground mines.

[5] It must be a historical quirk that oil sand open pit mining is not generally included in Canadian mining statistics. It should receive its own category alongside coal. Present day production from Syncrude and Suncor is almost the same as total production of metals, non-metals, construction (quarries), and coal combined. And oil sands production is poised to quadruple in size over the next decade.

[6] In 1999, there were 277 metal, nonmetal and coal mines, 3000 stone quarries, and sand and gravel pits in Canada. (Morrison, 2001)

[7] The total area of mining disturbed land in Canada since 1850 is estimated at less 400,000 hectares (Morrison, 2001) which corresponds to about 0.04 percent of the 1.01 billion hectare Canadian land mass.

Most mines have ongoing progressive reclamation but are only beginning to recognize the magnitude of the task of reclaiming the entire site. As shown below, few mines have experience in reclaiming more than individual patches of land on their sites. Data on average annual reclamation was harder to come by, especially since a lot of mines don't do annual reclamation. Figure 2.12 shows that those reporting annual rates range from 10 to 300 hectares per year, with a lot in the range of 20 to 50 hectares per year.

While recognizing the importance of progressive reclamation, many sites will have the bulk of their closure and reclamation work left until after active mining stops. As described later, most mines are unprepared to deal with the magnitude of the work that remains after closure and often resort to dormancy instead of completing their closure plan.

Figures 2.13 and 2.14 show the mining rate (tonnes per day) versus disturbed area. Not surprisingly, larger daily production rates lead to larger disturbed areas, and a crude rule of thumb is that mines produce about 2000 hectares of disturbance for each 100,000 tonnes per day of material (ore and waste) mined.

John Gadsby points out that given the relatively low percentage of a commodity (metal, coal, bitumen) in the host rock, the volume of waste is generally 10 to 10,000 times that of the ore – mines are really in the business of waste management. Furthermore, the aerial extent of waste in the final landscape is generally several times that of the mined-out pit (a sort of aerial swell factor) for most kinds of mining. Reclamation and closure planning is usually dominated by these waste materials.

Of note, the number of abandoned mines runs into the hundreds of thousands – a number that vastly outnumbered active and dormant mines. While this appendix focuses mainly on active and dormant mines, many of the sites visited came into the abandoned category. Most states and provinces have programs for remediating abandoned mines, which usually goes under the banner of abandoned mine lands (AML). The information presented in this appendix will apply to those state-run AML organizations. Curiously, AML programs are modest with modest funding and landscape performance goals, yet the regulators usually expect more from privately owned mines. Some of the greatest innovations are presently coming from AML programs.

Figure 2-1 Map view of mine site locations visited

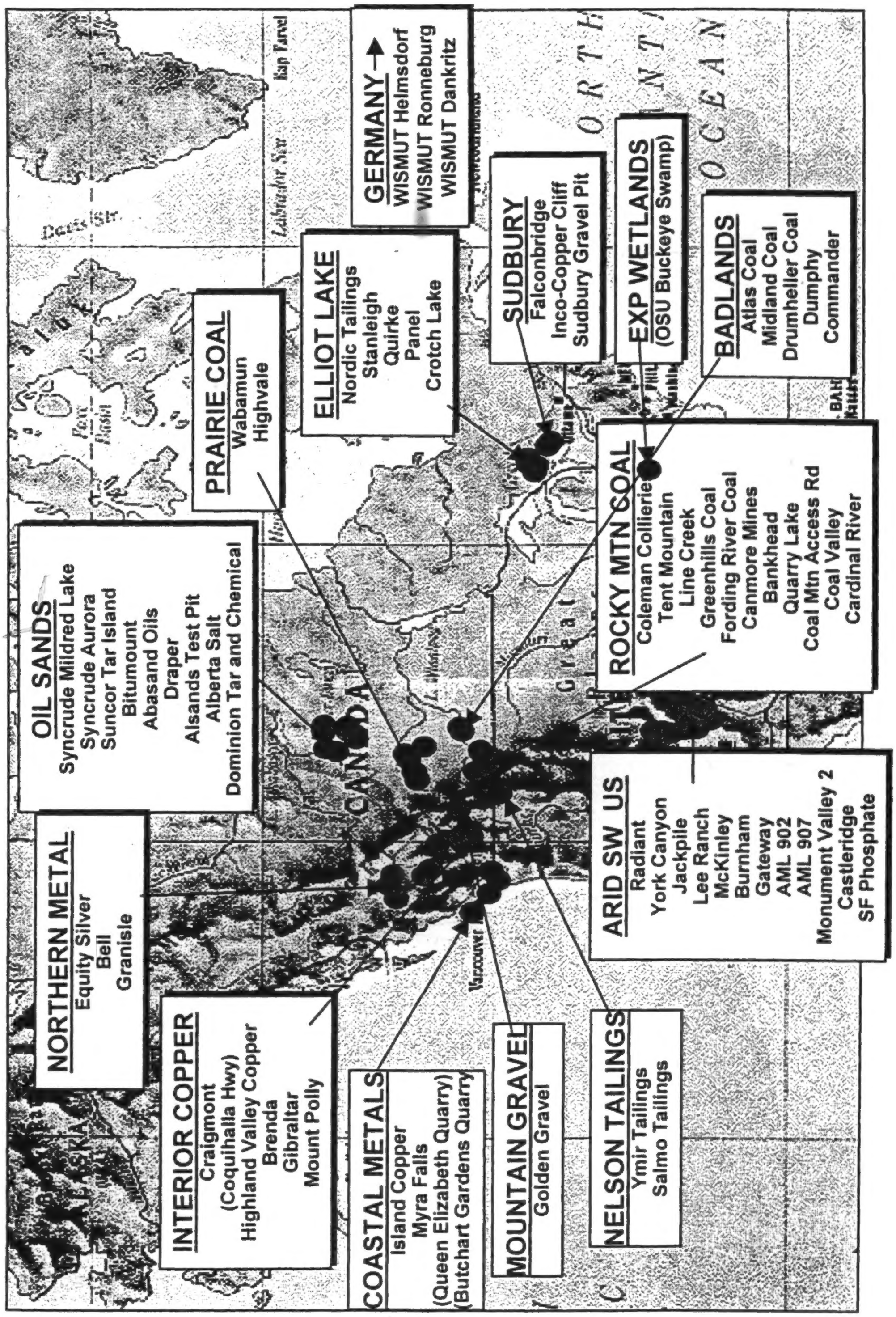
GERMANY →
WISMUT Helmsdorf
WISMUT Ronneburg
WISMUT Dankritz
ELLIOT LAKE
Nordic Tailings
Stanleigh
Quirke
Panel
Crotch Lake
SUDBURY
Falconbridge
Inco-Copper Cliff
Sudbury Gravel Pit
EXP WETLANDS
(OSU Buckeye Swamp)
BADLANDS
Atlas Coal
Midland Coal
Drumheller Coal
Dumphy
Commander
PRAIRIE COAL
Wabamun
Highvale
ROCKY MTN COAL
Coleman Collieries
Tent Mountain
Line Creek
Greenhills Coal
Fording River Coal
Canmore Mines
Bankhead
Quarry Lake
Coal Mtn Access Rd
Coal Valley
Cardinal River
OIL SANDS
Syncrude Mildred Lake
Syncrude Aurora
Suncor Tar Island
Bitumount
Abasand Oils
Draper
Alsands Test Pit
Alberta Salt
Dominion Tar and Chemical
NORTHERN METAL
Equity Silver
Bell
Granisle
ARID SW US
Radiant
York Canyon
Jackpile
Lee Ranch
McKinley
Burnham
Gateway
AML 902
AML 907
Monument Valley 2
Castleridge
SF Phosphate
INTERIOR COPPER
Craigmont
(Coquihalla Hwy)
Highland Valley Copper
Brenda
Gibraltar
Mount Polly
COASTAL METALS
Island Copper
Myra Falls
(Queen Elizabeth Quarry)
(Butchart Gardens Quarry)
MOUNTAIN GRAVEL
Golden Gravel
NELSON TAILINGS
Ymir Tailings
Salmo Tailings
CANADA
Vancouver
Davis Str.
Labrador Sea
Kap Farvel
Foxe Basin
ATLANTIC OCEAN

Figure 2.2 Number of mines visited versus region

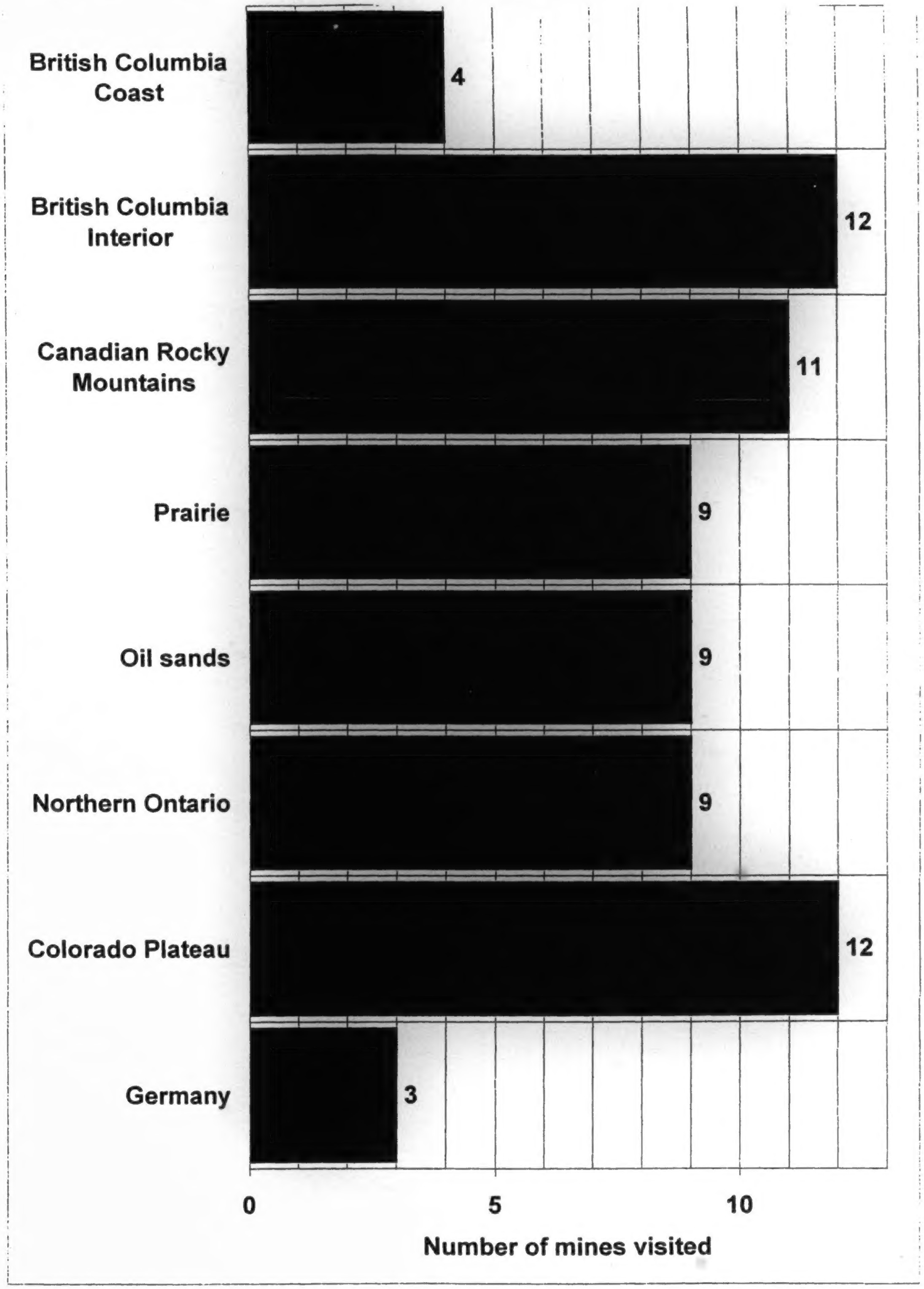

Figure 2.3 **Mine precipitation**

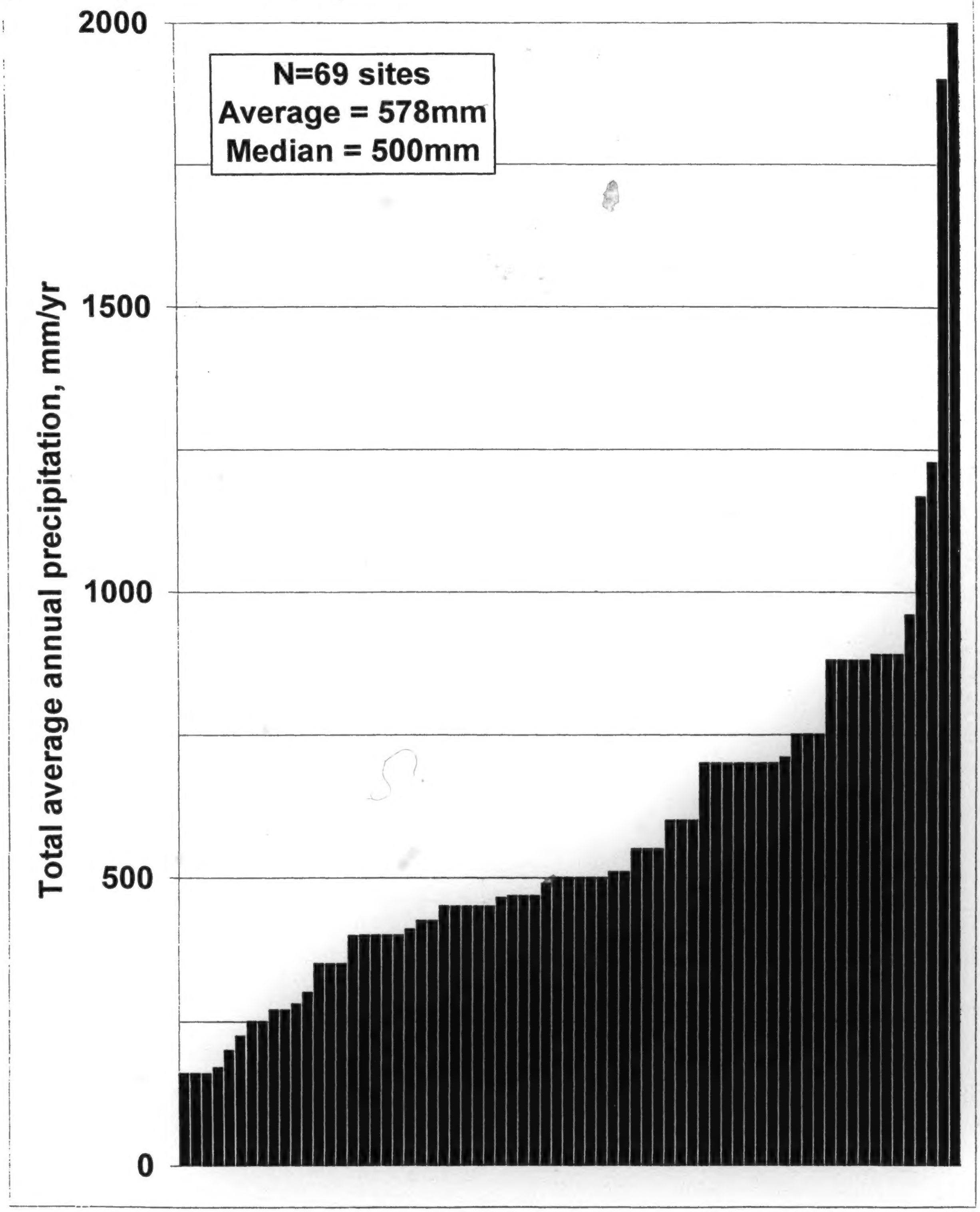

Figure 2.4 Mining method

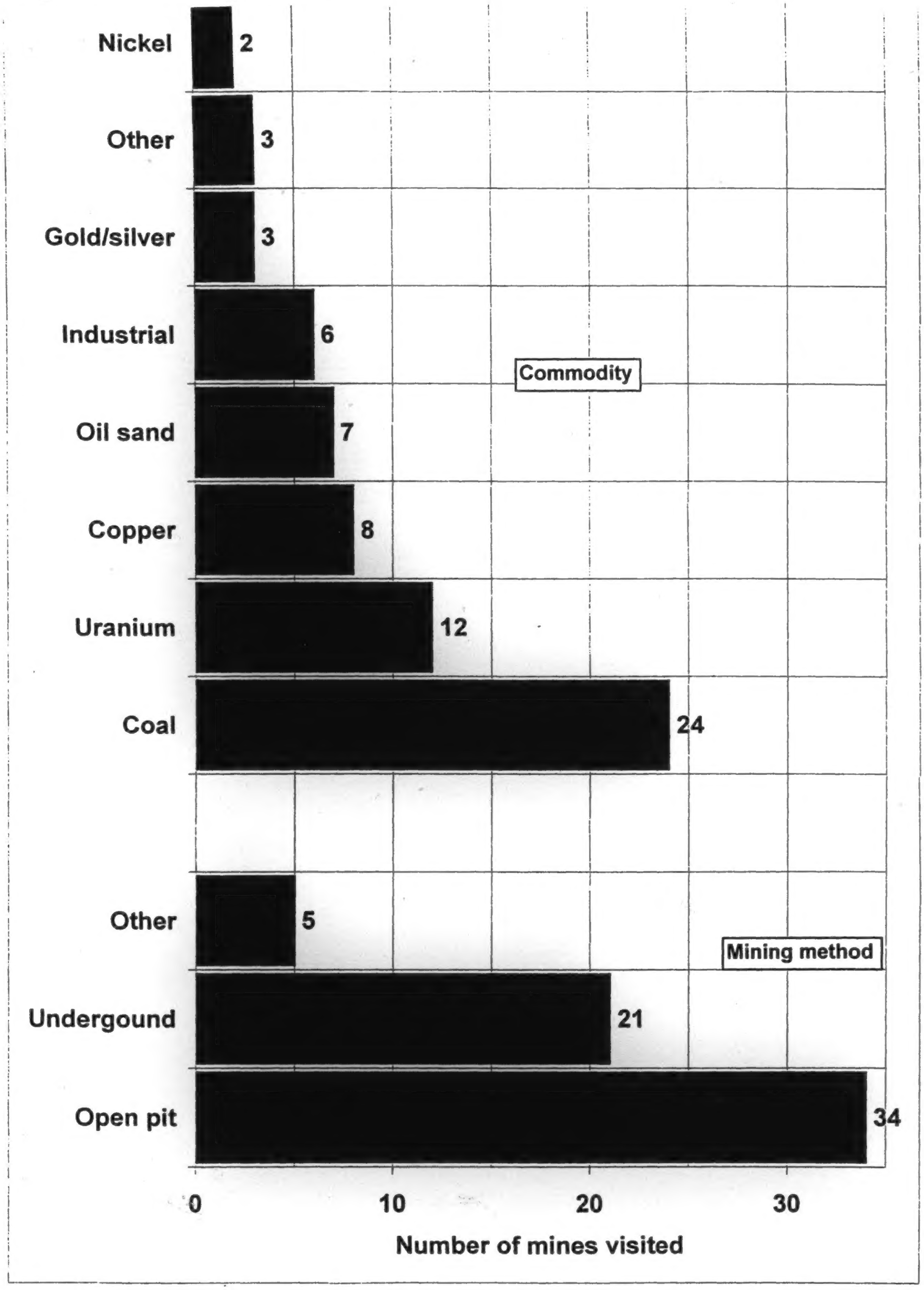

Figure 2.5 Mine date opening

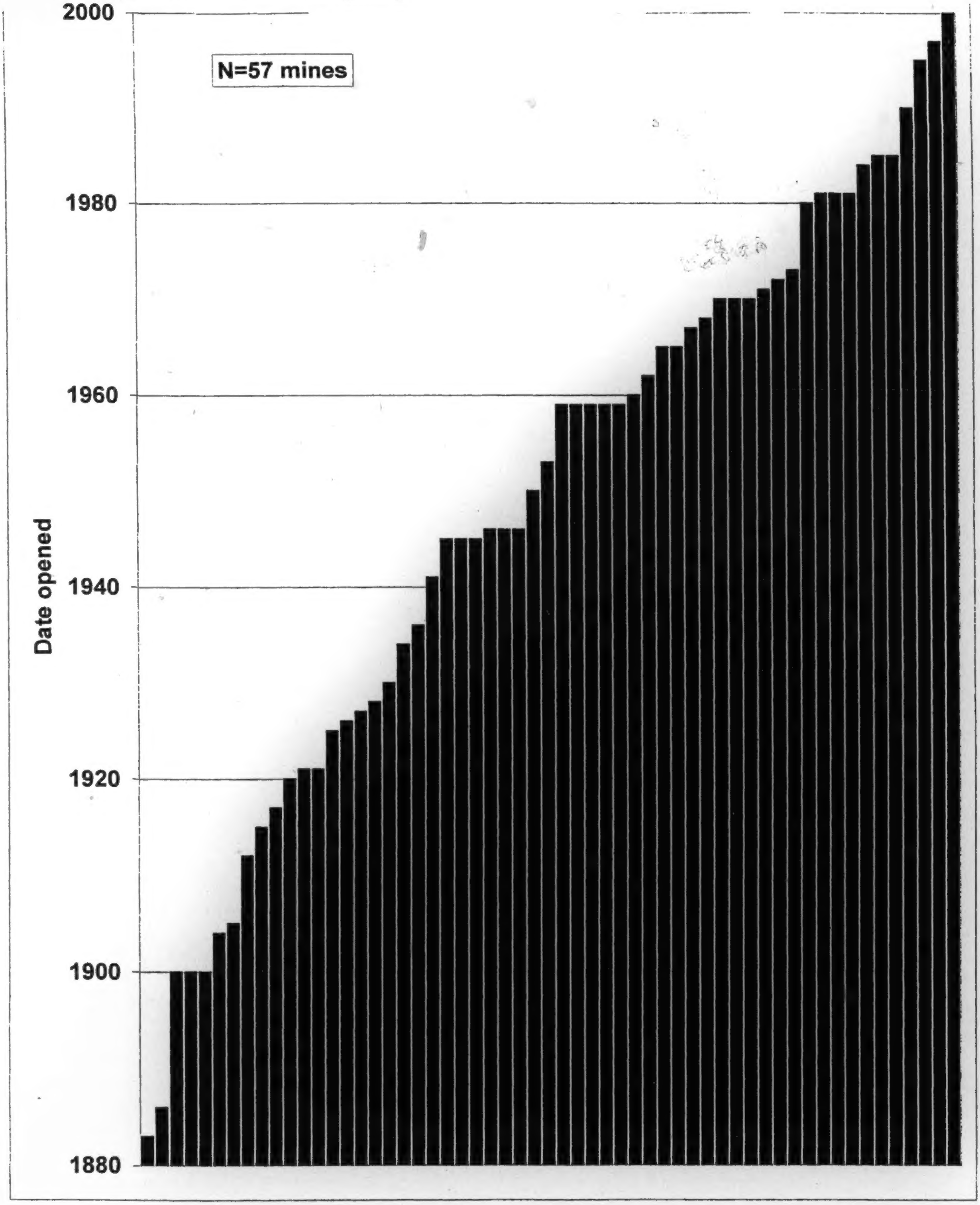

Figure 2.6 Mine date closing

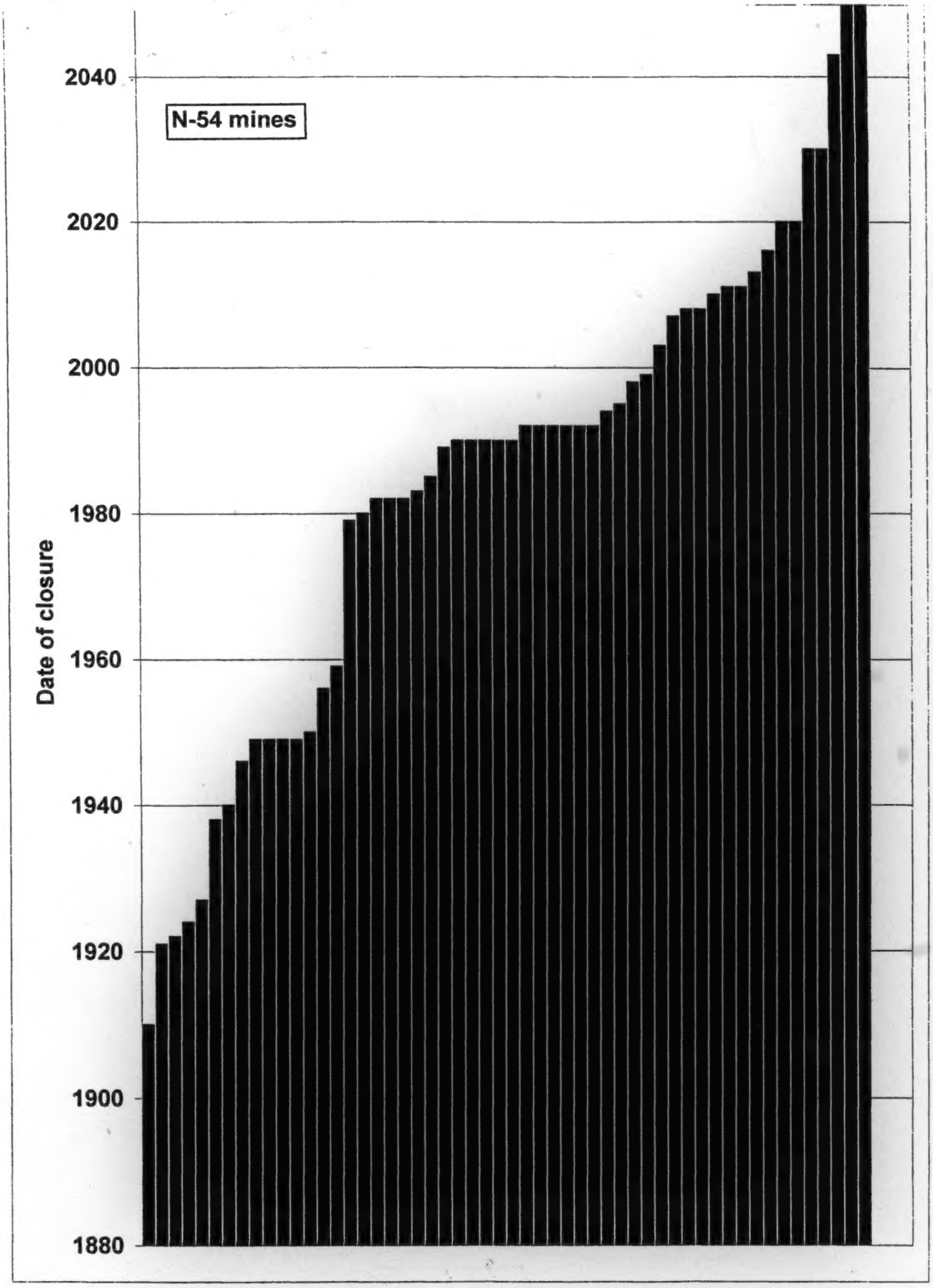

Figure 2.7 Mine opening versus closing

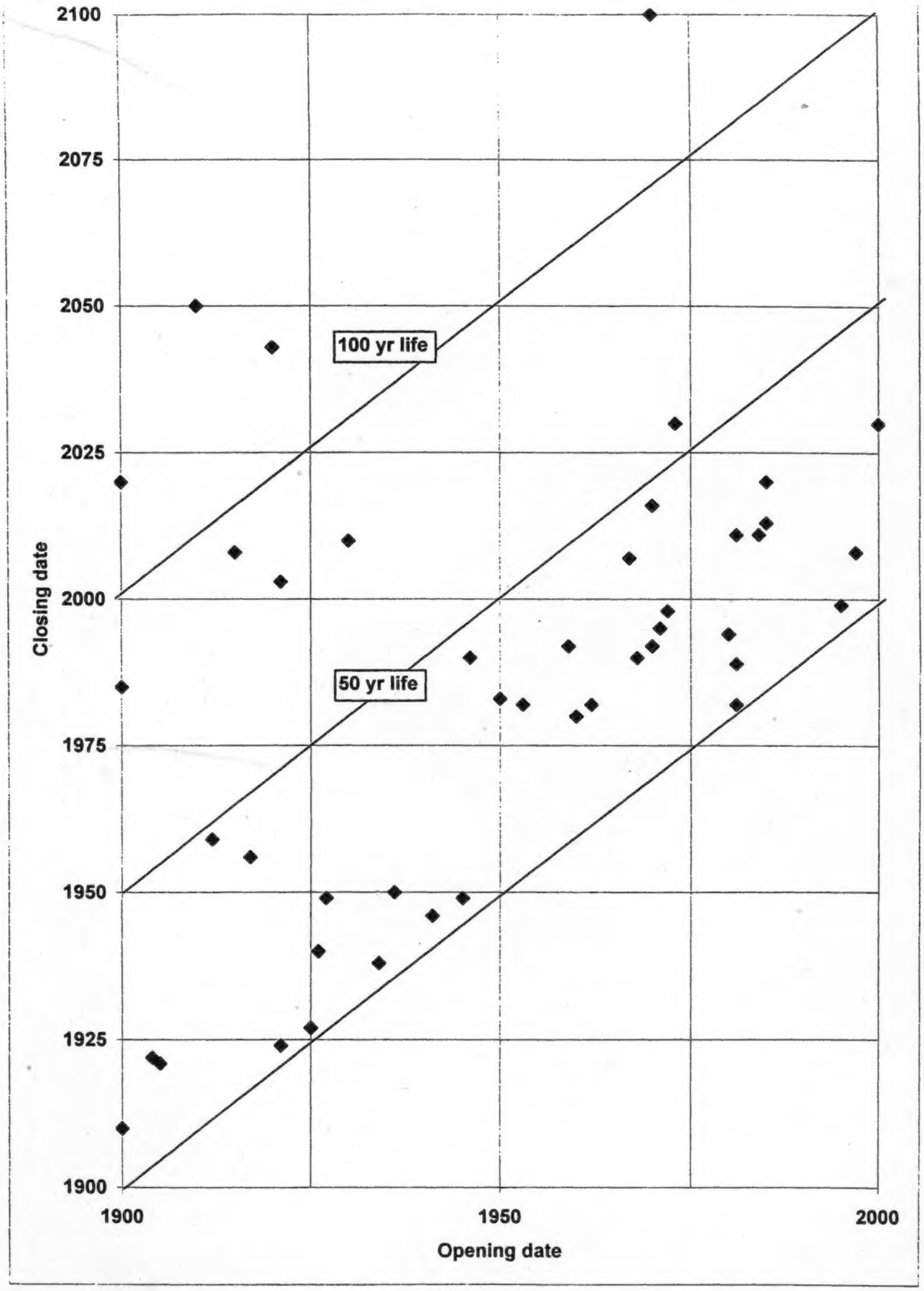

Figure 2.8 Total tonnes mined per day (arithmetic)

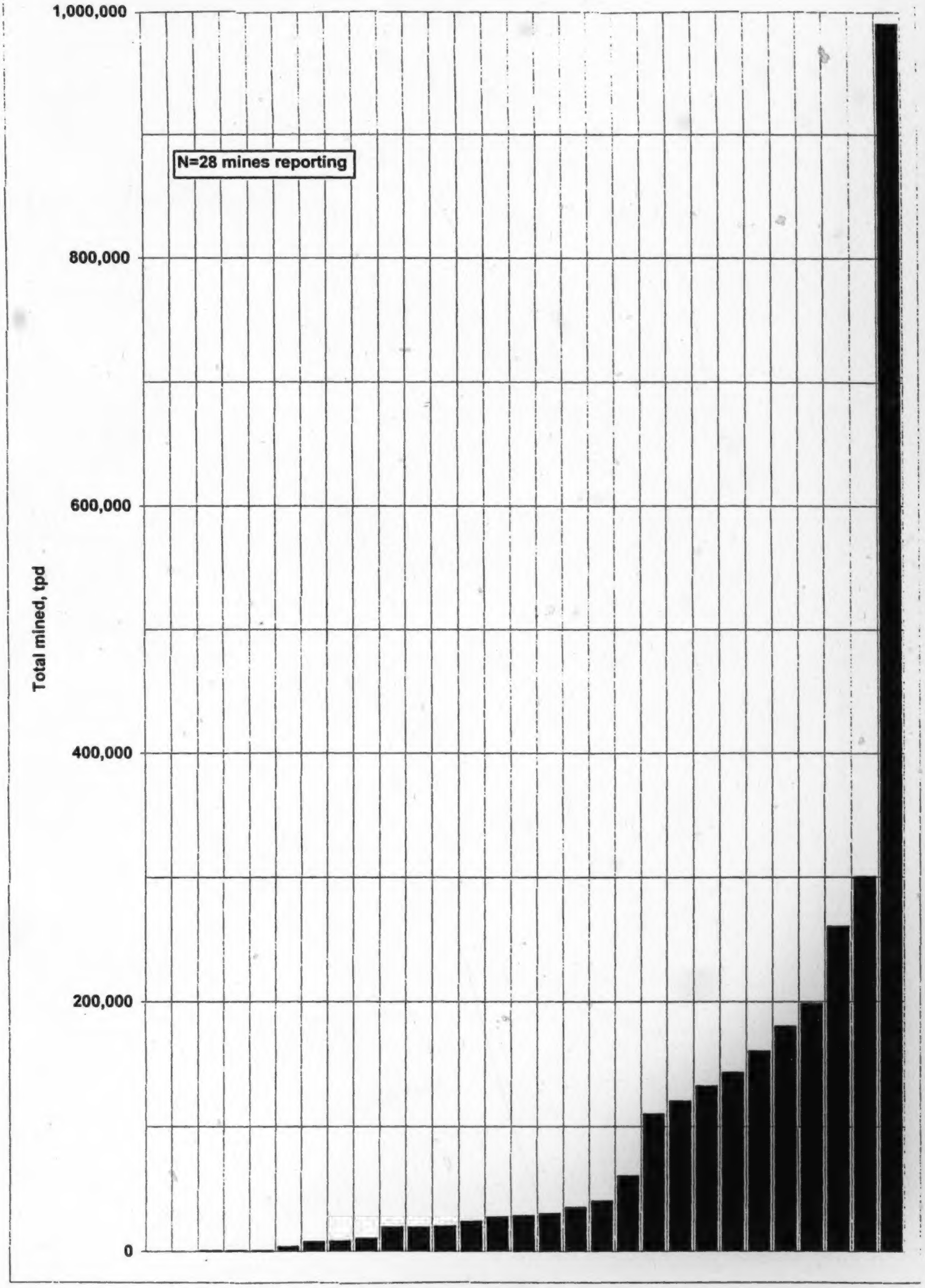

Figure 2.9 Total tonnes mined per day (logarithmic)

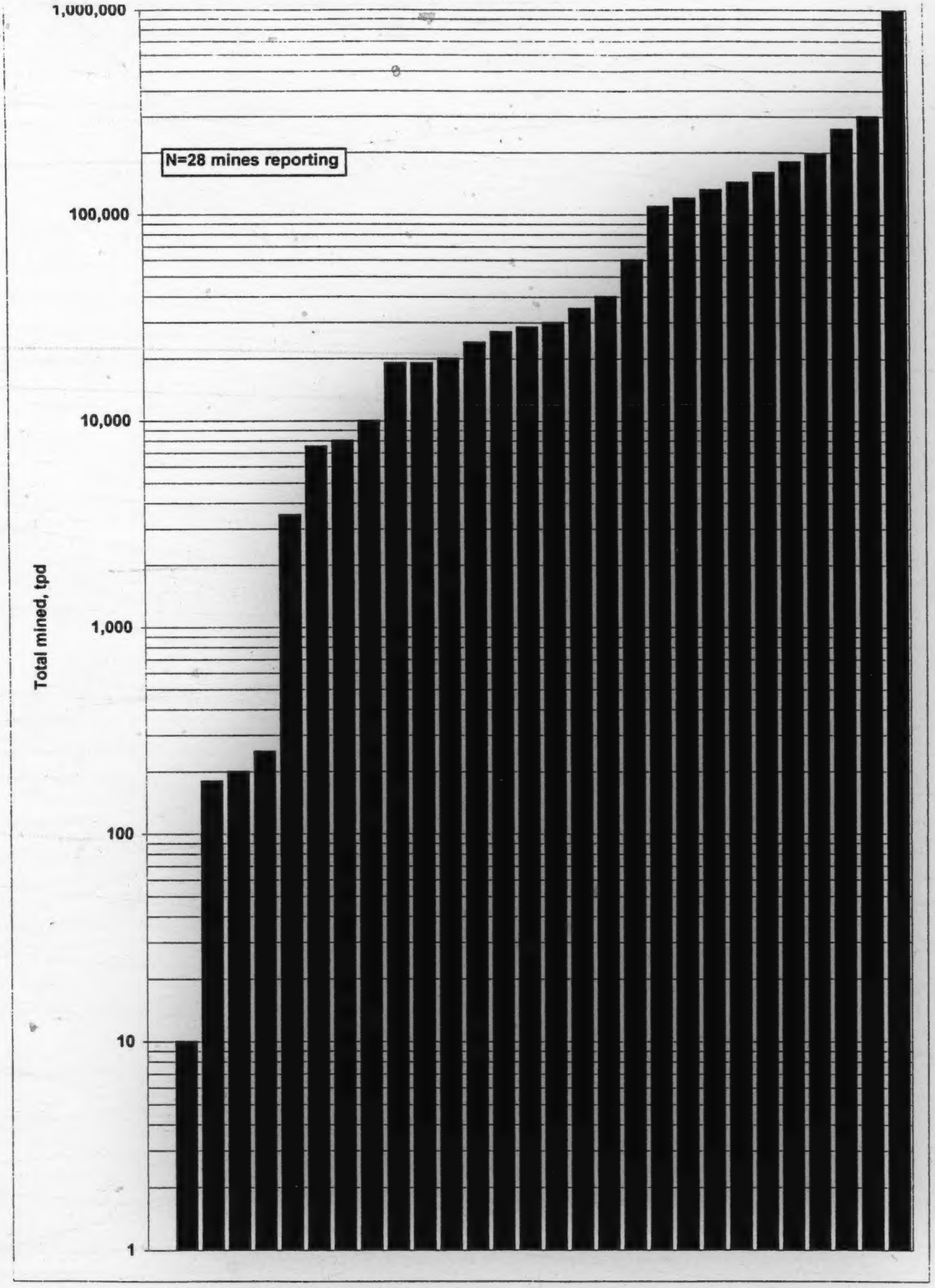

Figure 2.10 Disturbed and reclaimed areas of mines visited (arithmetic scales)

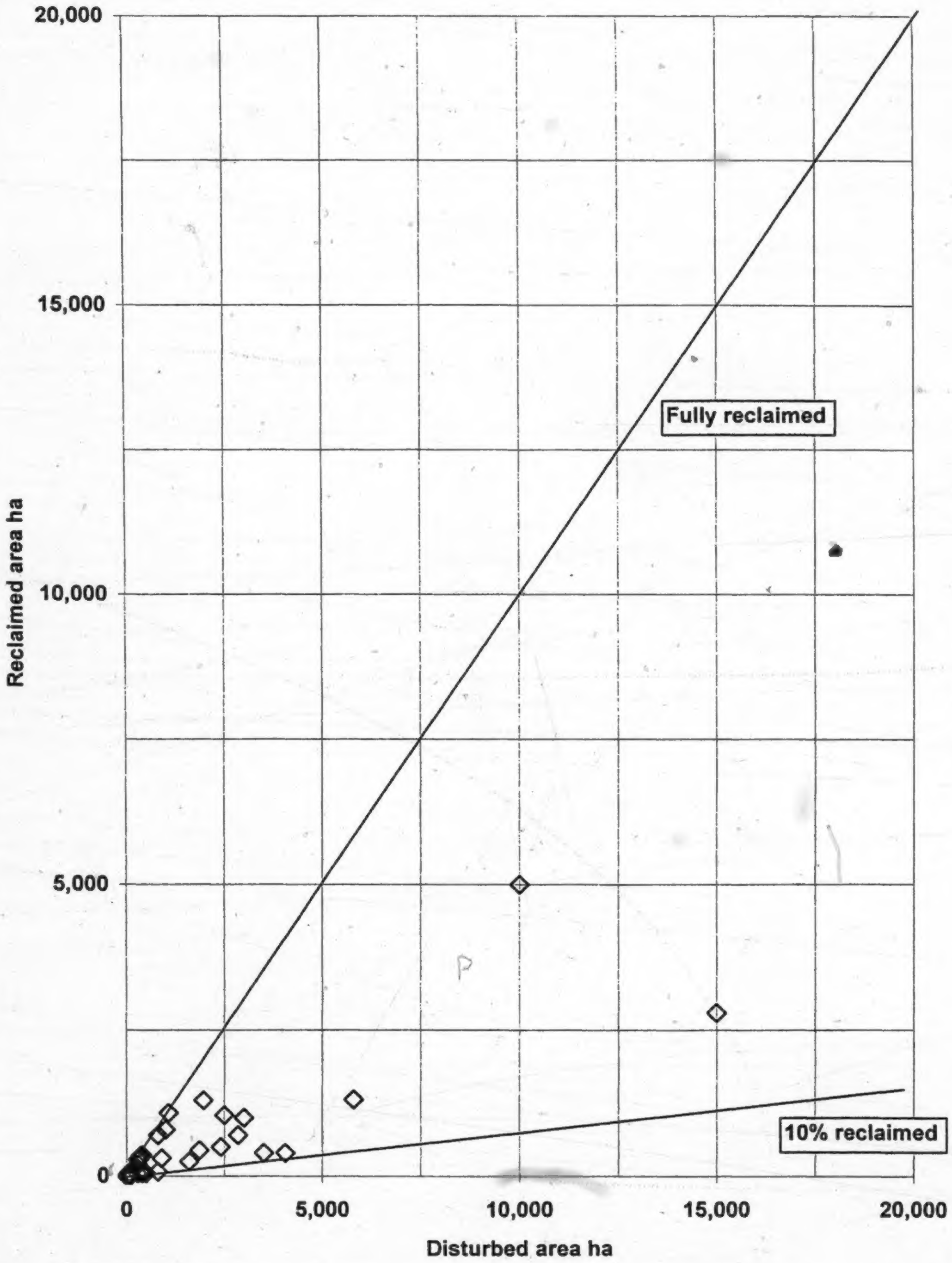

Figure 2.11 Disturbed and reclaimed areas of mines visited (logarithmic scales)

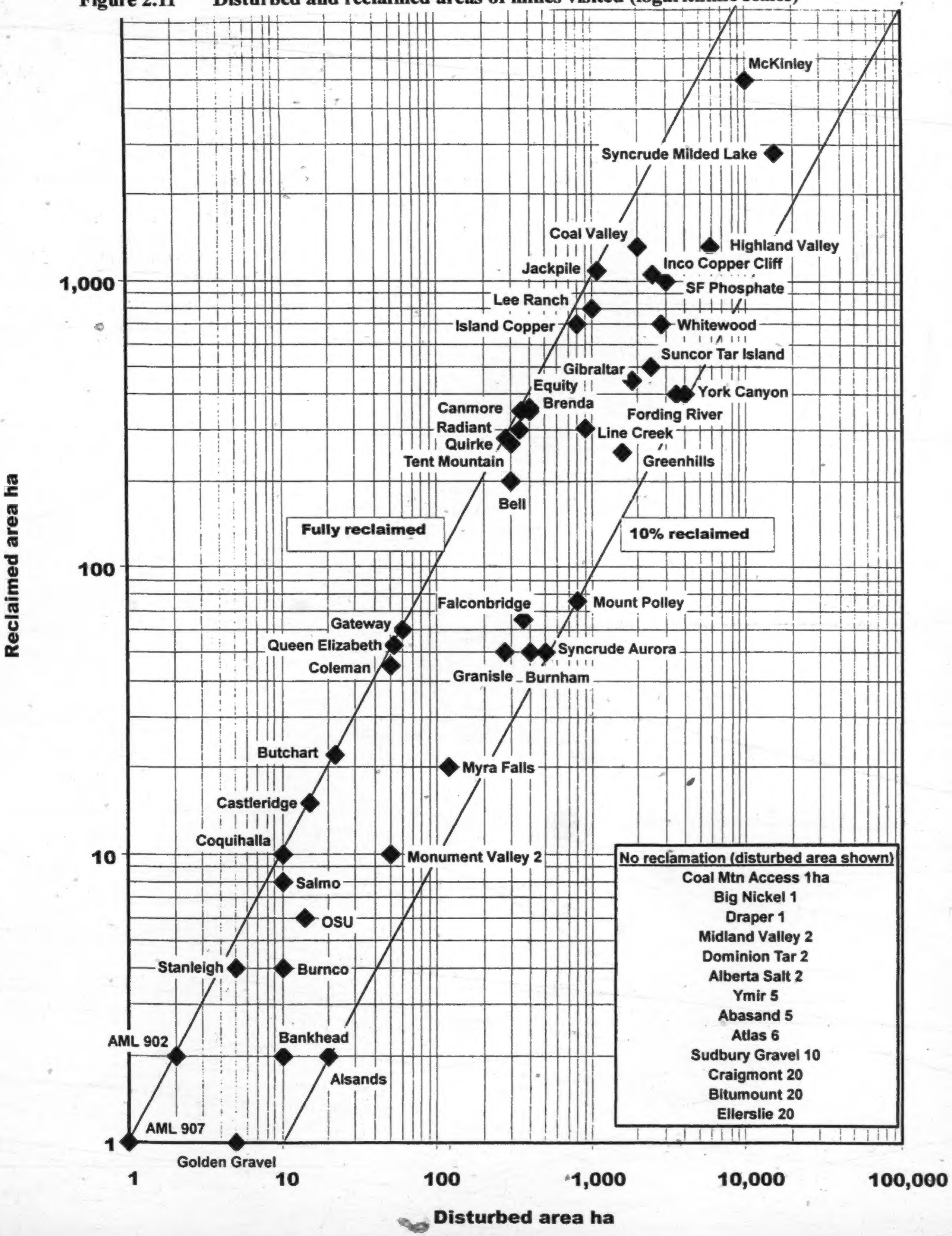

Figure 2.12 **Annual reclamation rate**

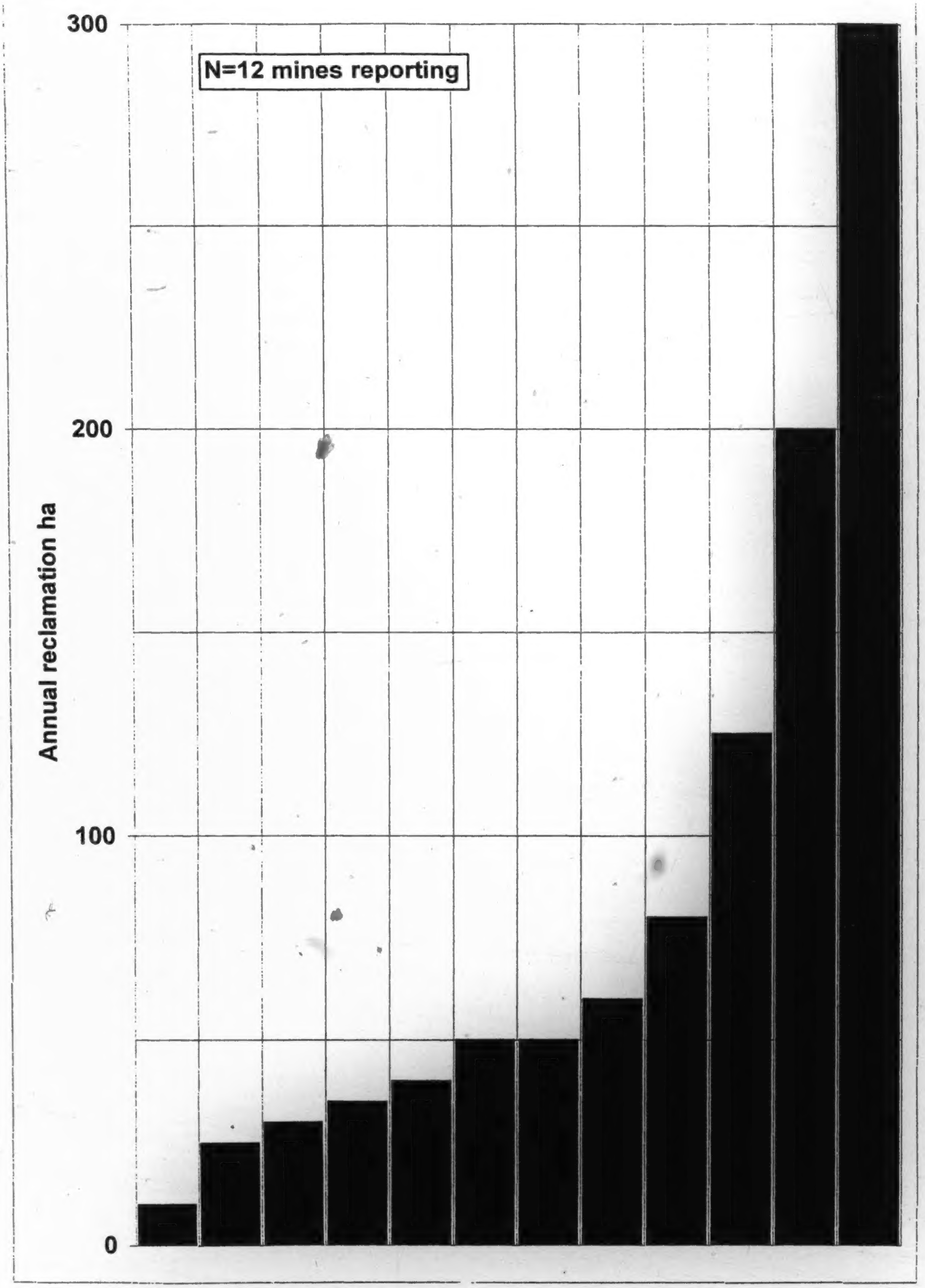

Figure 2.13 Mining rate versus disturbed area (arithmetic)

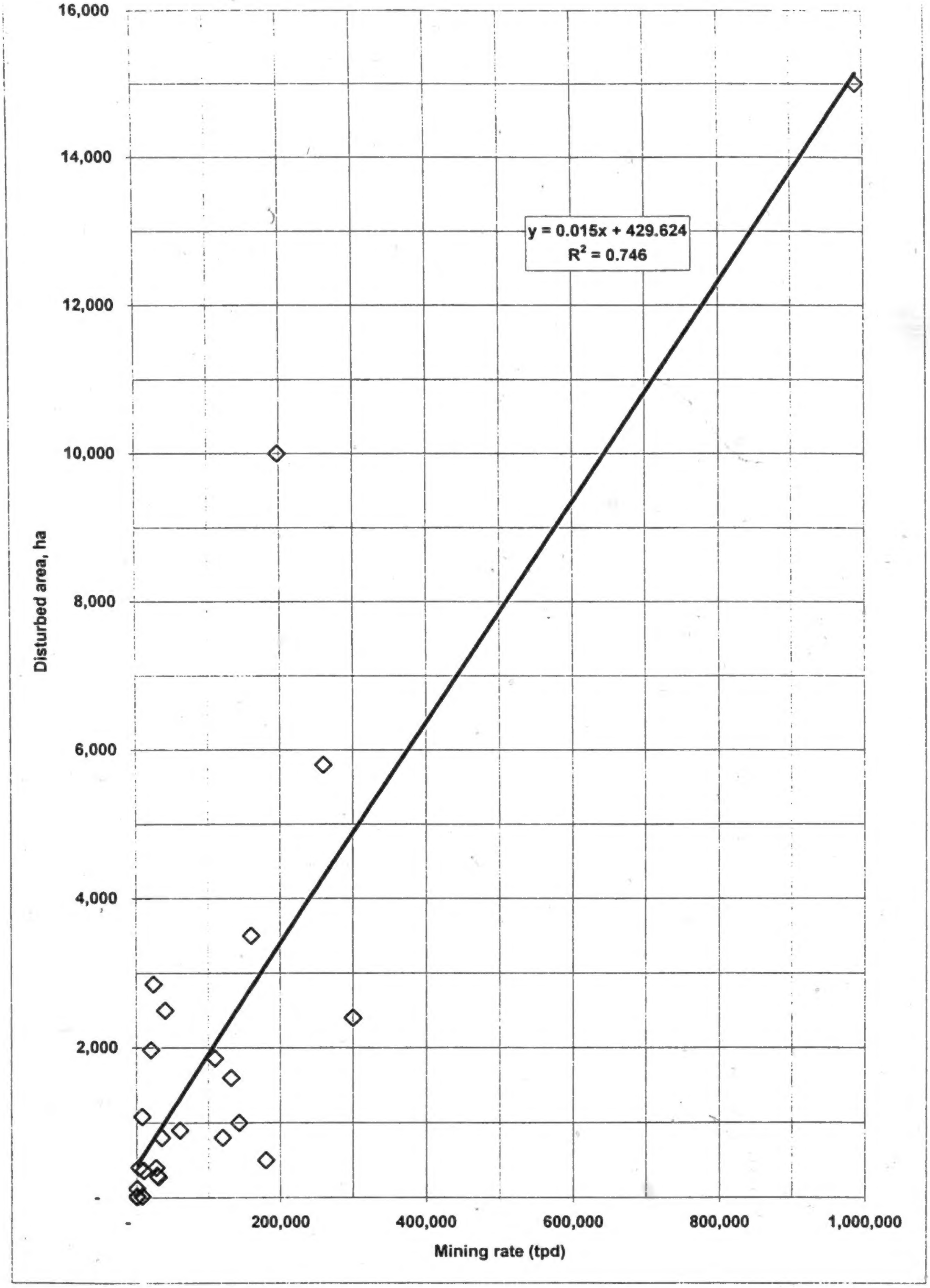

Figure 2.14 Mining rate versus disturbed area (logarithmic)

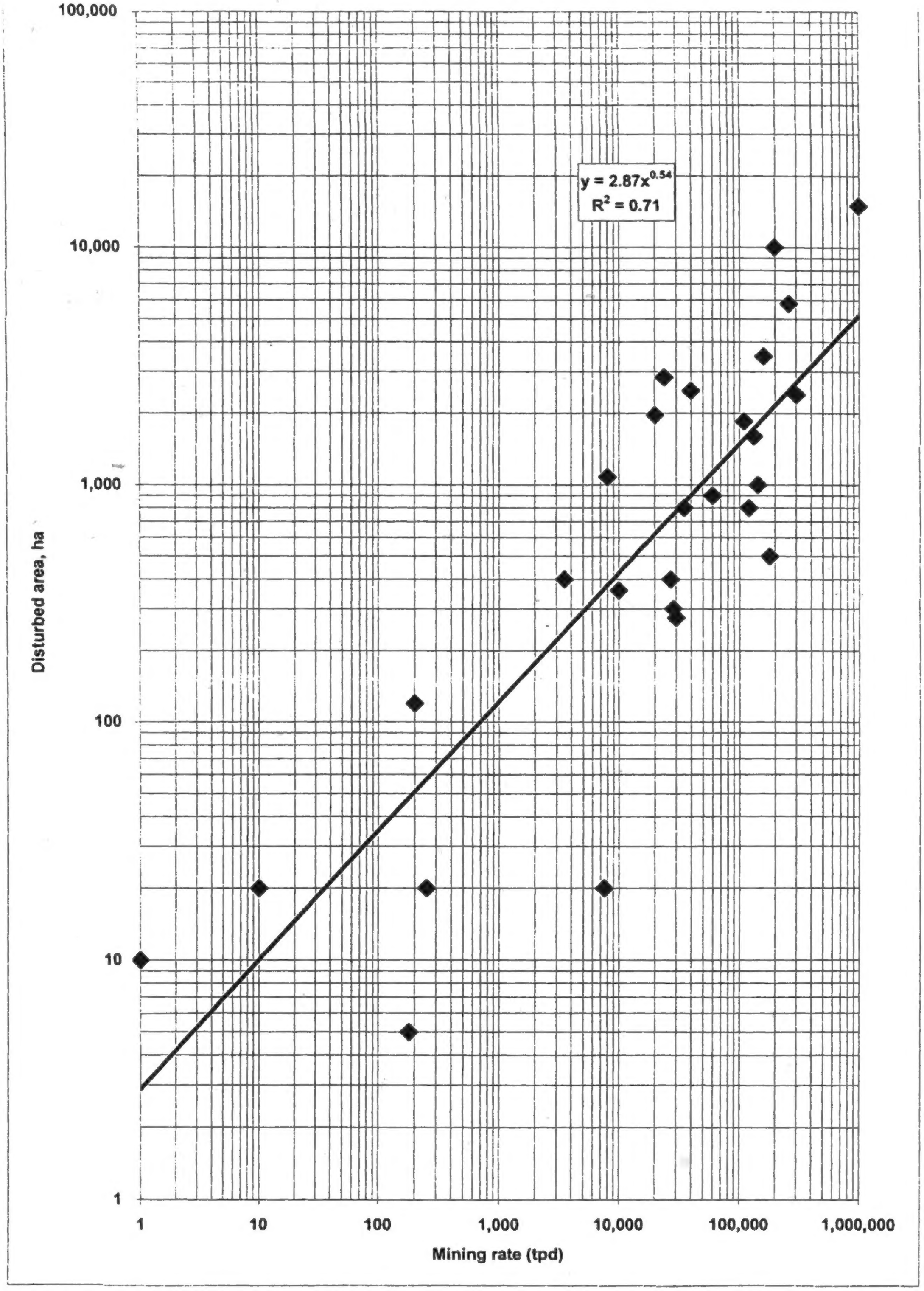

Plate 2.1 **Mines visited ranged from 100 to 2000 millimetres of average annual rainfall.**

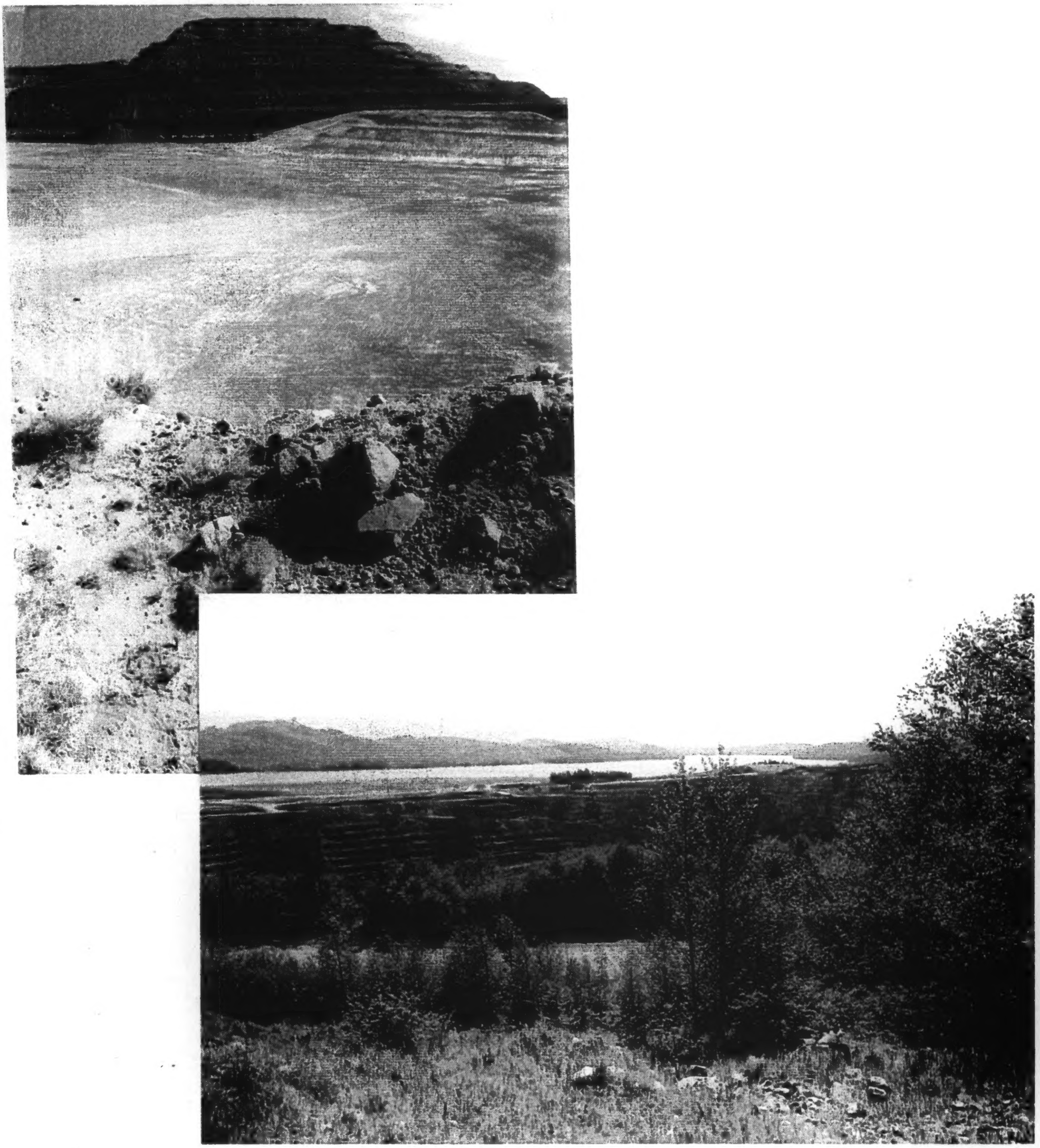

Plate 2.2 A legacy of a hundred years of mining – dormant open pits, dumps, and underground workings at an active underground metal mine in a rainforest.

Table 2.1 Minesites and their locations

Name	Type	Status	Nearest locality	Province / State	Latitude °	Longitude °	Elevation ft / masl	Region	Major ores	Total mined (tonnes per day)	Disturb-ed area (ha)	Reclaim ed area (ha)
Island Copper	Open-pit copper	Closure	Port Hardy	BC	50.60	127.47	50 /10	British Columbia Coast	Cu, Mo, Au, Ag	120000	800	700
Myra Falls	Open-pit and underground metal	Active	Campbell River	BC	49.57	125.60	1,600 / 500	British Columbia Coast	Cu, Zn, Au, Ag	200	120	20
Tod Inlet (Buchart Gardens)	Limestone quarry	New reclamation	Victoria	BC	48.57	123.47	100 / 30	British Columbia Coast	Limestone		22	22
Queen Elizabeth Park Quarry	Rock quarry	New reclamation	Vancouver	BC	49.30	123.11	501 / 150	British Columbia Coast	Road rock		53	53
Equity Silver	Open and underground metal	Closure	Houston	BC	54.19	126.26	4,000 / 1200	British Columbia Interior	Ag, Au, Cu	27000	400	360
Bell	Open-pit copper	Closure	Granisle	BC	55.03	126.23	2,500 / 750	British Columbia Interior	Cu, Ag, Au	28500	300	200
Granisle	Open-pit copper	Dormant	Granisle	BC	54.94	126.16	2,500 / 750	British Columbia Interior	Cu, Ag, Au	30000	275	50
Gibraltar	Open-pit copper	Dormant	McLease Lake	BC	52.52	122.29	4,000 / 1200	British Columbia Interior	Cu, Mo, Ag		1860	445
Mount Polley	Open-pit gold	Active	Likely	BC	52.56	121.64	3,600 / 1100	British Columbia Interior	Cu, Au	35000	800	76
Highland Valley Copper	Open-pit copper	Active	Logan Lake	BC	50.50	120.98	5,000 / 1500	British Columbia Interior	Cu	260000	5800	1315
Craigmont	Re-mining magnetite	Active	Merrit	BC	50.21	120.92	4,000 / 1200	British Columbia Interior	Magntite	7500	20	0
Coquihalla Hwy	Highway cuts	Active	Merrit	BC	50.17	120.67	4,000 / 1200	British Columbia Interior		10		10
Brenda	Open-pit copper	Closure	Peachland	BC	49.88	120.00	4,800 / 1500	British Columbia Interior	Cu, Mo	3500	400	350
Cardinal River Coals	Open-pit coal	Active	Hinton	AB	53.08	127.42	5,500 / 1700	Canadian Rocky Mountains	Coal			
Salmo Tailings	Underground metal	Abandoned	Salmo	BC	49.23	127.26	2,300 / 700	British Columbia Interior	Ag, Au, Pb, Zn	1	10	8

Name	Type	Status	Nearest locality	Province / State	Latitude °	Longitude °	Elevation ft / masl	Region	Major ores	Total mined (tonnes per day)	Disturb-ed area (ha)	Reclaimed area (ha)
Ymir Tailings	Underground metal	Abandoned	Ymir/Nelson	BC	49.28	127.21	2,500 / 750	British Columbia Interior	Ag, Au, Pb, Zn		5	0
Golden Gravel	Gravel pit	Abandoned	Golden	BC	51.25	126.83	2,600 / 800	Canadian Rocky Mountains	Gravel		5	1
Coal Valley	Open-pit coal	Active	Edson	AB	53.08	126.80		Canadian Rocky Mountains	Coal		1970	1300
Quarry Lake	Quarry	Care and maintenance	Canmore	AB	51.42	125.87	4,500 / 1400	Canadian Rocky Mountains	Coal?		10	10
Bankhead Coal Mines	Underground coal	Museum	Banff	AB	51.20	125.53	5,000 / 1500	Canadian Rocky Mountains	Coal		10	2
Canmore Mines	Underground coal	New reclamation	Canmore	AB	51.06	125.33	4,300 / 1300	Canadian Rocky Mountains	Coal		350	350
Greenhills Coal	Open-pit copper	Active	Sparwood	BC	50.11	124.87	6,000 / 1800	Canadian Rocky Mountains	Coal	132000	1600	250
Fording River Coal	Open-pit copper	Active	Sparwood	BC	50.22	124.86	6,000 / 1800	Canadian Rocky Mountains	Coal	160000	3500	400
Line Creek Coal	Open-pit copper	Active	Sparwood	BC	49.92	124.78	5,000 / 1500	Canadian Rocky Mountains	Coal	60000	900	306
Coal Mountain Access Road	Highway cuts	Dormant	Sparwood	BC	49.67	114.77	4,200 / 1300	Canadian Rocky Mountains			1	0
Tent Mountain Coal	Open-pit coal	Dormant	Coleman	AB	49.57	124.70	6,000 / 1800	Canadian Rocky Mountains	Coal		300	270
Coleman Collieries	Coal processing	Closure	Coleman	AB	49.63	124.52	4,400 / 1300	Canadian Rocky Mountains	Coal		50	45
Highvale Coal	Open-pit coal	Active	Wabamun	AB	53.51	124.56	2,400 / 700	Prairie	Coal	19000		
Burnco Gravel Nose Hill	Gravel pit	Active	Calgary	AB	51.10	124.12	4,000 / 1200	Prairie	Gravel		10	4
Whitewood Coal (Wabamun)	Open-pit coal	Active	Wabamun	AB	53.10	124.10	2,400 / 750	Prairie	Coal		2850	700
Ellerslie Coal	Underground coal	Abandoned	Edmonton	AB	53.44	123.49	2,600 / 800	Prairie	Coal		20	0
Dumphy Mine	Underground coal	Abandoned	Drumheller	AB	51.48	122.86	2,400 / 750	Prairie	Coal			

Name	Type	Status	Nearest locality	Province / State	Latitude °	Longitude °	Elevation ft / masl	Region	Major ores	Total mined (tonnes per day)	Disturb-ed area (ha)	Reclaimed area (ha)
Commander (Nacmine) Mine Spoils	Underground coal	Abandoned	Drumheller	AB	51.46	122.77	2,400 / 750	Prairie	Coal			
Midland Valley Coal	Underground coal	Museum	Drumheller	AB	51.50	122.76	2,400 / 750	Prairie	Coal		2	0
Atlas Coal	Underground coal	Museum	Drumheller/ East Coulee	AB	51.34	122.48	2,300 / 700	Prairie	Coal		6	0
Bitumount	Open-pit oil sands	Museum	Fort McMurray	AB	57.37	121.62	1000 / 300	Oil sands	Oil sand	10	20	0
OSU Wetlands	Research Area	New reclamation	Columbus	OH	40.00	- 83.02	900 / 300	Prairie	Research		14	6
Syncrude Mildred Lake	Open-pit oil sands	Active	Fort McMurray	AB	57.04	121.62	1,000 / 300	Oil sands	Oil sand	990000	15000	2800
Alsands test pit	Open-pit oil sands	Dormant	Fort McMurray	AB	57.19	121.54	1,100 / 300	Oil sands	Oil sand	250	20	2
Syncrude Aurora	Open-pit oil sands	Active	Fort McMurray	AB	57.31	121.51	1,000 / 300	Oil sands	Oil sand	180000	500	50
Suncor Tar Island	Open-pit oil sands	Active	Fort McMurray	AB	56.97	121.48	900 / 300	Oil sands	Oil sand	300000	2400	500
Alberta Salt Company	Solution mining	Abandoned	Fort McMurray	AB	56.71	121.40	870 / 250	Oil sands	Salt		3	0
Abasand Oils	Open-pit oil sands	Museum	Fort McMurray	AB	56.72	121.38	850 / 250	Oil sands	Oil sand	180	5	0
Dominion Tar and Chemical Company	Solution mining	Abandoned	Fort McMurray	AB	56.69	111.32	870 / 250	Oil sands	Salt		3	0
Draper	Open-pit oil sands	Museum	Fort McMurray	AB	56.66	111.25	1,150 / 350	Oil sands	Oil sand		1	0
Castleridge 1-4	Open-pit coal	Closure	Helper	UT	39.69	110.86	6,000 / 1800	Colorado Plateau	Coal		15	15
Monument Valley 2	Underground uranium	Closure	Mexican Hat	UT	36.95	109.75	5,000 / 1500	Colorado Plateau	Uranium		50	10
AML 907	Underground uranium	Closure	Bluff	UT	37.07	109.59	5,000 / 1500	Colorado Plateau	Uranium		1	1
AML 902	Underground uranium	Closure	Bluff	UT	37.07	109.56	5,000 / 1500	Colorado Plateau	Uranium		2	2
SF Phosphate	Open put phosphate	Active	Vernal	UT	40.60	109.54	6,300 / 1900	Colorado Plateau	Phosphate		3000	1000
McKinley	Open-pit coal	Active	Window Rock	NM	35.70	108.87	5,000 / 1500	Colorado Plateau	Coal	198000	10000	5000
Burnham	Open-pit coal	Dormant	Newcomb	NM	36.42	108.41	5,000 / 1500	Colorado Plateau	Coal		400	50

Name	Type	Status	Nearest locality	Province / State	Latitude °	Longitude °	Elevation ft / masl	Region	Major ores	Total mined (tonnes per day)	Disturb-ed area (ha)	Reclaimed area (ha)
Gateway	Open-pit coal	Closure	Est. Wilderness	NM	36.26	108.24	5,800 / 1800	Colorado Plateau	Coal		60	60
Lee Ranch	Open-pit coal	Active	Ambrosial Lake	NM	35.40	107.83	5,000 / 1500	Colorado Plateau	Coal	143000	1000	800
Jackpile	Open-pit uranium	Closure	Paguate	NM	35.14	107.37	5,000 / 1500	Colorado Plateau	Uranium	8000	1080	1080
Radiant	Open-pit coal	New reclamation	Florence	CO	38.40	105.12	5,000 / 1500	Colorado Plateau	Coal		280	280
York Canyon	Open-pit coal	Active	Raton	NM	36.93	104.75	5,000 / 1500	Colorado Plateau	Coal		4050	5000
Stanleigh	Underground uranium	Care and maintenance	Elliot Lake	ON	46.42	82.63	1,150 / 350	Northern Ontario	Uranium		5	4
Quirke	Underground uranium	Care and maintenance	Elliot Lake	ON	46.50	82.62	1,200 / 350	Northern Ontario	Uranium		340	300
Crotch Lake	Underground uranium	Care and maintenance	Elliot Lake	ON	46.42	82.58	1,000 / 300	Northern Ontario	Uranium		15	15
Nordic Tailings	Underground uranium	Care and maintenance	Elliot Lake	ON	46.38	82.58	1,200 / 350	Northern Ontario	Uranium		10	10
Panel	Underground uranium	Care and maintenance	Elliot Lake	ON	46.47	82.55	1,200 / 350	Northern Ontario	Uranium		10	10
Inco-Copper Cliff Tailings and Smelter	Underground nickel	Active	Sudbury	ON	46.48	81.07	1,150 / 350	Northern Ontario	Ni, Cu	40000	2500	1045
Big Nickel	Underground museum	Museum	Sudbury	ON	46.48	81.02	1,150 / 350	Northern Ontario			1	0
Falconbridge Sudbury Smelter	Underground nickel	Active	Sudbury	ON	46.58	80.81	1,150 / 350	Northern Ontario	Ni	10000	360	65
Sudbury Airport Gravel Pit	Gravel pit	Dormant	Sudbury	ON	46.63	80.80	1,125 / 350	Northern Ontario	Gravel		10	0
WISMUT Helmsdorf	Uranium Mine tailings	Closure	Helmsdorf	Germany	51.29	10.35 E	2,500 / 750	Germany	Uranium			110
WISMUT Ronneburg	Uranium Mine tailings	Closure	Ronneburg	Germany	50.86	12.18 E	2,500 / 750	Germany	Uranium		1670	
WISMUT Dankritz	Uranium Mine tailings	Closure	Dankritz	Germany	50.78	12.42 E	2,500 / 750	Germany	Uranium			

Table 2.2 Checklist of questions used for mine visits

Category	Short name	Detail
Mine data	Name	Common name of the mine
	Type	Major mining method and ore
	Status	One of abandoned, active, care and maintenance, closure, dormant, museum, new reclamation)
Cultural information	Nearest locality	Nearest town or city
	Province / State	Province of state that the mine is located in
	Nearest Highway	Nearest primary or secondary highway
	Mine owner	Name of the mining company that owns the mine
Location	Latitude (deg)	Latitude (all latitudes are north of the equator)
	Longitude (deg)	Longitude (all longitudes are west of the prime meridian (except for the three German mines)
	Elevation (ft)	Average elevation above sea level
Natural region	Region	Regional setting of mine, one of BC Coast, BC Interior, Canadian Rocky Mountains, Prairie, Colorado Plateau, Northern Ontario, Germany)
	Local topography	The general local topography of the minesite
Climate	Precipitation (mm)	Average annual precipitation at or near the site
	% as snow	Percent of precipitation as snow (water equivalent basis)
	Temperatures	General range of temperatures experienced at the mine
	Frost	Whether there is frost action at the mine
	Climatic region	General climatic region
Tour info	Date	Date visited
	Guide	Name of the person who acted as a guide
	Who visited	Initials of the people visiting the mine
Key dates	Opened	Date that the mine opened
	Closed	Date that the mine closed
	To close	Date that the mine plans to close
	Planned/operating years	Number of operating years (or planned years)
Mine data	Shifts	How much the mine is open.
	Max # employees	The historical peak number of employees at the mine
	Final workforce	The number of employees at the mine just prior to closure
	Closure workforce	The number of employees at the mine during closure
	Ores	The major ores produced by the mine
	Tonnes ore per day	The ore production rate, tonnes per day.

Category	Short name	Detail
	Strip ratio x:1	The strip ratio (the ratio of overburden to ore)
	Total mined per day, tpd	Total mine production (ore plus overburden) per day
	Mining method	Generalized mining method
Reclamation	Disturbed area (ha)	The total disturbance by the mine, in hectares
	Reclaimed area	The total area reclaimed by the mine, in hectares
	% reclaimed	The ratio of reclaimed to disturbed area, in percent.
	Annual reclamation (ha)	Typical rates of annual reclamation, in hectares per year
	Resloping	The amount of resloping of dumps and highwalls by mine
	Typical slope angles (x:1)	Typical resloping angles
	Typical slope angles (deg)	Typical resloping angles
	Cover soil thickness (m)	The thickness of capping material is generally placed on mine waste, in metres
	Direct seeding (% area)	The amount of area that has waste or bare area directly seeded (without capping)
	Agronomic species	Whether agronomic species are used for reclamation
	Native species	Whether native species are used for reclamation
	Natural invasion	Whether natural invasion of native species is occurring
	Planted trees	Whether trees are planted in reclamation
	Stocked with fish	Whether waterbodies are stocked with fish
	Research plots	Whether there are special reclamation research plots
	Reference areas	Whether there are undisturbed reference areas being monitored
Monitoring	Climate station	Whether there is a local climate station
	Stream flows	Whether stream flows are being monitored
	Wells	Whether groundwater is being monitored with wells or piezometers
	Vegetation	Whether vegetation is being monitored
	Erosion	Whether erosion is being monitored
	Animals	Whether animals or wildlife are being monitored
	Remote sensing	Whether the mine uses remote sensing for monitoring
Landforms	Streams	Performance of reclaimed streams
	Mine-pit lake	Performance of mine-pit lakes
	Highwalls	Performance of highwalls
	Portals and shafts	Performance of portals and shafts
	Talus	Performance of talus slopes
	Resloped dumps	Performance of resloped dumps
	Repose dumps	Performance of mine dumps at their angle of repose
	Tailings pond	Performance of tailings pond (plateau) areas

Category	Short name	Detail
	Tailings slopes	Performance of slopes of tailings dams
	Slope terraces	Performance of terraces on slopes
	Flat dump	Performance of dump plateaus
	Roads	Performance of roads
	Rockdrains	Performance of rock drains
	Sed ponds	Performance of sedimentation ponds
	Fences	Performance of fences
	Micro-topography	Performance of microtopography (specially created roughness or small mounds)
	Meso-topography	Performance of meso-topography (broad ridges and swales on dumps).
	Wetlands	Performance of constructed wetlands
	Flat bare disturbed areas	Performance of bare disturbed areas
Hydrology	Flood design/ short term (1/x year)	The design flood recurrence interval for short term (operations)
	Flood design/ long term (1/x year)	The design flood recurrence interval for long term (closure)
	Pit filling	How well pit filling is proceeding (end pit lake)
	Major streams	How major streams are designed
	Minor streams	How minor stream are designed
	Major Gradients (%)	The gradients of major streams
	Slope length (m)	The slope length of resloped dumps between terraces
	Checkdams	Whether checkdams are used
	Meshes	Whether erosion control meshes are used
	Rip rap durability	Whether there is a concern with rip rap durability
	Soft rip rap	
	Groundwater	Whether groundwater is a concern
	Geomorphic approach	Whether the geomorphic approach to landscape design is employed
	Infiltration	Whether infiltration is an important aspect of water management
	Enhanced infiltration	Whether the mine had specially created conditions to enhance infiltration
	Beaver problems	Whether there are likely to be problems with beaver dams in streams
Containment requirements	Capping required	Whether capping of mine wastes is required
	Spontaneous com	Whether spontaneous combustion (of coals) is a problem
	ARD?	Whether there is acid rock drainage problems
	Other chemicals	Whether there are other chemical concerns
	Chemical remediation	Whether chemical remediation is occurring (water treatment or soil treatment)

Category	Short name	Detail
Physical reclamation	Steep slopes	Whether steep excavated slopes are allowed to remain
	Buildings	Whether buildings are removed
	Foundations	Whether foundation are removed or buried
	Roads	Whether roads are reclaimed
Human threats to landscape performance	Trespassing	Whether trespassing is a threat to landscape performance
	Vandalism	Whether vandalism is a threat to landscape performance
	Nearest habitation (km)	Distance to the nearest settlement
	Illegal grazing	Whether illegal grazing is a threat to landscape performance
Maintenance strategies	Periodic monitoring	What frequency of monitoring is employed
	Maintenance style	What kind of maintenance style is employed (none, sporadic, as required, passive, active)
	Partition site?	Whether the site is partitioned into separate management areas
	Dam safety	Whether dam safety inspections will be required in long term
End land use goals	#1 end land use	The stated primary end land use for the site.
	Wildlife	The degree to which Wildlife is an end land use goal (primary, secondary)
	Agriculture / farming	The degree to which Agriculture / farming is an end land use goal (primary, secondary)
	Grazing/ranching	The degree to which Grazing/ranching is an end land use goal (primary, secondary)
	Re-mining	The degree to which Re-mining is an end land use goal (primary, secondary)
	Forestry	The degree to which Forestry is an end land use goal (primary, secondary)
	Municipal landfill	The degree to which having a municipal landfill is an end land use goal (primary, secondary)
	Parkland	The degree to which creating parkland is an end land use goal (primary, secondary)
	Just be stable	The degree to which just having a stable landscape is an end land use goal (primary, secondary)
	Lakes and ponds	The degree to which having lakes and ponds is an end land use goal (primary, secondary)
	Historic	The degree to which preserving a historic site (museum) is an end land use goal (primary, secondary)
	Recreation	The degree to which Recreation is an end land use goal (primary, secondary)
	Hunting	The degree to which Hunting is an end land use goal (primary, secondary)
	Fishing	The degree to which Fishing is an end land use goal (primary, secondary)

Category	Short name	Detail
	Company owned	The degree to which the company simply retains ownership is an end land use goal (primary, secondary)
	Undetermined	The degree to which the end land use goal is undetermined (primary, secondary)
	Conflict with stability?	The degree to which the land use goal conflicts with stability of the landscape (primary, secondary)
	Human habitation	The degree to which human habitation is an end land use goal (primary, secondary)
	Visual appeal	The degree to which having a visually appealing landscape is an end land use goal (primary, secondary)
	Industrial areas	The degree to which having an industrial area is an end land use goal (primary, secondary)
	Green - natural	The degree to which being a natural / green area is an end land use goal (primary, secondary)
	Research	The degree to which research activity is an end land use goal (primary, secondary)
Closure planning practice	Regulations	Whether regulations require closure planning
	Stakeholders	The degree to which stakeholders are involved in reclamation / closure planning
	Reclamation status	The status of reclamation (abandoned, active, care and maintenance, closure, dormancy, museum, new reclamation)
	Closure plan	Whether there is a closure plan
	$ for closure (magnitude)	The magnitude of closure costs
	Greatest innovation	The greatest innovation of the mine with respect to closure and reclamation
	Greatest challenge	The greatest challenge faced by the mine with respect to closure and reclamation
	#1 Closure issue	The stated primary closure issue
	#1 uncertainty	The stated primary uncertainty
	Closure infogap	The degree to which information was lost between the period of operation and closure
	Type of closure leader	The background of the person who is leading closure activities (biologist, forester or farmer, geo-specialist (geologist, geotechnical engineer, geomorphologist), hydrologist, civil engineer, mining engineer, mining foreman, historian, team, no one)
	Facilities for closure	What kinds of infrastructure is available or created for closure
	Linear access	Whether there is a long access road to the site to maintain
	PR	Whether there are public relations activities related to reclamation and closure
Bonding requirements	Reclamation	Whether there is reclamation bonding required.
	Closure	Whether there is bonding for post closure.
	Liability	How the mines view long-term liability

Category	Short name	Detail
Closure goals	Active maintenance landscape	The degree to which Active maintenance landscape is an end land use goal or strategy (primary, secondary)
	Avoid declination or certificate	The degree to which Avoid declination or certificate is an end land use goal or strategy (primary, secondary)
	Avoid dusting	The degree to which Avoid dusting is an end land use goal or strategy (primary, secondary)
	Avoid fencing	The degree to which Avoid fencing is an end land use goal or strategy (primary, secondary)
	Avoid gullying	The degree to which Avoid gullying is an end land use goal or strategy (primary, secondary)
	Avoid hard erosion control measures	The degree to which Avoid hard erosion control measures is an end land use goal or strategy (primary, secondary)
	Avoid human habitation	The degree to which Avoid human habitation is an end land use goal or strategy (primary, secondary)
	Avoid physical hazards to users	The degree to which Avoid physical hazards to users is an end land use goal or strategy (primary, secondary)
	Avoid spontaneous com	The degree to which Avoid spontaneous com is an end land use goal or strategy (primary, secondary)
	Avoid vandalism	The degree to which Avoid vandalism is an end land use goal or strategy (primary, secondary)
	Cover / containment	The degree to which Cover / containment is an end land use goal or strategy (primary, secondary)
	Create employment	The degree to which Create employment is an end land use goal or strategy (primary, secondary)
	Create industrial landfills	The degree to which Create industrial landfills is an end land use goal or strategy (primary, secondary)
	Create research site	The degree to which Create research site is an end land use goal or strategy (primary, secondary)
	Create water holes for livestock	The degree to which Create water holes for livestock is an end land use goal or strategy (primary, secondary)
	Create wetlands	The degree to which Create wetlands is an end land use goal or strategy (primary, secondary)
	Create dormant closure condition	The degree to which Create dormant closure condition is an end land use goal or strategy (primary, secondary)
	Dormancy -- holding pattern	The degree to which Dormancy -- holding pattern is an end land use goal or strategy (primary, secondary)
	Encourage fish	The degree to which Encourage fish is an end land use goal or strategy (primary, secondary)
	Encourage game	The degree to which Encourage game is an end land use goal or strategy (primary, secondary)
	Encourage wildlife	The degree to which Encourage wildlife is an end land use goal or strategy (primary, secondary)
	Future mining	The degree to which Future mining is an end land use goal or strategy (primary, secondary)

Category	Short name	Detail
	Forestry	The degree to which Forestry is an end land use goal or strategy (primary, secondary)
	Geotechnical stability	The degree to which Geotechnical stability is an end land use goal or strategy (primary, secondary)
	Historical preservation	The degree to which Historical preservation is an end land use goal or strategy (primary, secondary)
	Meet bioproductivity level	The degree to which Meet bioproductivity level is an end land use goal or strategy (primary, secondary)
	Meet slope regulations	The degree to which Meet slope regs is an end land use goal or strategy (primary, secondary)
	Meet soil capability regulations	The degree to which Meet soil capability regs is an end land use goal or strategy (primary, secondary)
	Meet soil chemistry regulations	The degree to which Meet soil chemistry regs is an end land use goal or strategy (primary, secondary)
	Meet solids loading regulations	The degree to which Meet solids loading regs is an end land use goal or strategy (primary, secondary)
	Meet subsidence regulations	The degree to which Meet subsidence regs is an end land use goal or strategy (primary, secondary)
	Meet vegetation regulations	The degree to which Meet vegetation regs is an end land use goal or strategy (primary, secondary)
	Meet water quality regulations	The degree to which Meet water quality regs is an end land use goal or strategy (primary, secondary)
	Mimic reference area	The degree to which Mimic reference area is an end land use goal or strategy (primary, secondary)
	Mimic natural geomorphology	The degree to which Mimic natural geomorphology is an end land use goal or strategy (primary, secondary)
	Minimize active maintenance costs	The degree to which Minimize active maintenance costs is an end land use goal or strategy (primary, secondary)
	Mitigate to where nature takes over	The degree to which Mitigate to where nature takes over is an end land use goal or strategy (primary, secondary)
	No or lesser liability	The degree to which No or lesser liability is an end land use goal or strategy (primary, secondary)
	Passive Maintenance landscape	The degree to which Passive Maintenance landscape is an end land use goal or strategy (primary, secondary)
	PR	The degree to which PR is an end land use goal or strategy (primary, secondary)
	Provide biodiversity	The degree to which Provide biodiversity is an end land use goal or strategy (primary, secondary)
	Reclamation bond release	The degree to which Reclamation bond release is an end land use goal or strategy (primary, secondary)
	Regulatory approval	The degree to which Regulatory approval is an end land use goal or strategy (primary, secondary)
	Re-mining	The degree to which Re-mining is an end land use goal or strategy (primary, secondary)

Category	Short name	Detail
	Removal of infrastructure	The degree to which Removal of infrastructure is an end land use goal or strategy (primary, secondary)
	Remove physical hazards	The degree to which Remove physical hazards is an end land use goal or strategy (primary, secondary)
	Restore spirituality	The degree to which Restore spirituality is an end land use goal or strategy (primary, secondary)
	Retribution	The degree to which Retribution is an end land use goal or strategy (primary, secondary)
	Return land good as or better	The degree to which Return land good as or better is an end land use goal or strategy (primary, secondary)
	Return of land	The degree to which Return of land is an end land use goal or strategy (primary, secondary)
	Satisfy stakeholders	The degree to which Satisfy stakeholders is an end land use goal or strategy (primary, secondary)
	Self-sustaining landscape	The degree to which Self-sustaining landscape is an end land use goal or strategy (primary, secondary)
	Sell buildings and equipment	The degree to which Sell buildings and equipment is an end land use goal or strategy (primary, secondary)
	Tourism	The degree to which Tourism is an end land use goal or strategy (primary, secondary)
	Enhance visual aspects	The degree to which Enhance visual aspects is an end land use goal or strategy (primary, secondary)
	Walk away unreclaimed	The degree to which Walk away unreclaimed is an end land use goal or strategy (primary, secondary)
	Maintenance free	The degree to which Maintenance free is an end land use goal or strategy (primary, secondary)

3.0 FINDINGS: PLANNING AND RECLAMATION PRACTICE

3.1 Closure planning activities

Driven by regulatory requirements, most operating mines have prepared a first or even second-generation closure plan in the last five years – closure planning is becoming the norm for the mining industry. Though mines and their consultants are becoming more experienced in closure planning, they would benefit from a more comprehensive approach.

As the findings indicate, closure planning is most beneficial when it is done before a mine starts, but the focus of mining activity is seldom on closure planning in the development stages. A bit more effort in this period would pay off tremendously. Where real problems occur is at closure, when the closure plan is often set aside and the site goes into dormancy with most of the landscape unreclaimed.

Mines need to get on the closure path, using the plans as guides for decisions and interim plans, updating closure plans periodically and following through on commitments in a timely and diligent manner.

3.1.1 Contents of typical closure plans

Typical closure plans are 100 to 200 page documents with a series of large closure maps of the minesite appended. Typical costs of assembling such reports are $200,000[8] and they take several months to develop.

Most closure planning documents have the same general format. They briefly describe the mine operation, list the regulatory requirements (goals), present the reclamation plan, timing, schedule and costs, and describe the predicted performance of the closure landscape, relative to the regulatory requirements for the site. If there is one major issue, such as acid rock drainage (ARD), there is additional effort devoted to describing the science and engineering to deal with this concern.

Of particular interest to regulators are the costs for closure as these are usually used to estimate bonding costs. Debate rages as to how to best estimate these costs. The mines generally believe the costs should be based upon orderly closure over time. Regulators are often more interested in the instantaneous cost of closure, as if the mine stopped production overnight and started reclamation tomorrow. Some jurisdictions ask the mines to estimate the closure costs based on government wage rates, generally much higher than mining unit costs. Many mines don't want to show their costs, as these closure plans become public documents. Some jurisdictions provide spreadsheets with fixed unit costs, the mines just input the quantities and haul distances. Some areas are investigating the use of Monte Carlo simulations to determine the uncertainty in the costs. In reality, especially if reclamation and closure is to occur over several years or decades, costs can only be crudely estimated, and these more exacting methods do little to clarify the risks.

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[8] An interesting rule of thumb is that consultants reports often cost about $1000 per page (exclusive of appendices).

A few mines use artists' drawings to describe the landscape as many stakeholders have difficulty imagining the reclaimed landscape based on blueprints.

Geographical information systems (GIS) are becoming common at mines, usually first being used by the environmental department to keep track of monitoring data. A few mines have sophisticated systems that aid in their closure planning process.

Most of the mines visited had finished their first closure plans after many years of operation. Many of the key decisions that would affect long-term landscape performance were already made in the early days of mining, without much regard to closure. Of all the mines visited, only one new mine (Mount Polley) had a conceptual closure plan from the start. Comparing this mine to other nearby similar mines, it as apparent that perhaps the greatest benefit of a closure plan is the ability to determine the key risk areas and those requiring additional research.

3.1.2 Working with stakeholders

One learning that really stood out during the visits was how valuable it is to work with stakeholders and to include their needs in the final design. Involving stakeholders is a key element of successful reclamation and of good closure planning.

Mines demonstrated several techniques in this area.

- Work hard to identify all stakeholders and work with them individually. This requires a long-term commitment from management and an openness to act on suggestions.
- Work closely with regulators and support them as much as practical. Construction of closure landscapes has to be a team effort. The regulators are responsible for the good reclamation performance of the mine and poor performance reflects poorly on them.
- Maintain high levels of monitoring and environmental research so the mines know more than the regulators and other stakeholders. This allows mines to negotiate from a position of power and quickly fend off any unreasonable suggestions. For example, mine personnel in southeastern B.C. have become experts in wildlife habitat and typical wildlife patterns in their region. When stakeholders make suggestions – like creating certain kinds of habitat in unreasonable locations or statements regarding changing populations of animals – mine personnel can authoritatively provide the facts, supported by documentation right in the meetings. This provides more direct solutions that involve reasonable alternatives.
- Use reclamation sites for public relations opportunities. This might include bringing in stakeholders from other mines, constructing bus turnarounds and photo points, having family open house days, and even trophy fishing derbies in end-of-pit lakes.
- Some mines are using government scientists to provide research and development for reclamation technologies. The government scientists also provide advice for the regulators. Forming this alliance has numerous advantages – it fosters good communication and trust between the mine and the regulators, and can be a very successful strategy.

On the whole, mines do a poor job of public consultation. Their efforts are usually restricted to the minimum required by governments which generally includes open houses in local school gyms, advertised in the local paper, offering coffee and donuts. A few maps are posted on the walls, and a member of the mine makes a short presentation and fields questions. Mines are starting to recognize the importance and value of a good consultation program, and employ consultants who have expertise in these areas.

A particularly useful model is forming a local committee to provide guidance to one or more mines in the region in their reclamation and closure activities. The intent here is for the committee to identify the main goals that are important to local residents. Mines have great success with this activity in both learning from the community and sharing information with them. While some programs last a year or two and are used to decide specific issues, other programs are ongoing and involve regular meetings.

3.1.3 Stages in closure planning

Several stages to closure plan development and implementation are apparent. Each of these is described below.

- **No closure plan**

Most mines start with no closure plan, other than the knowledge that greening up the landscape and potentially restoring the site drainage will be necessary.

- **Conceptual closure plan**

The first step in establishing plans for closure is to make a conceptual closure plan. This has all the elements of a final closure plan but is conceptual in nature. A key tact in developing this conceptual plan is to be detailed enough to be complete yet, recognizing the plan will evolve and change over time, not too detailed.

The closure plan is usually developed by a closure leader, often the supervisor of the environmental department who is often a biologist by training. Use of consultants in developing the closure plan is also common. The closure plan usually uncovers or highlights costly deficiencies in the existing mine plans and often (unpleasantly) surprises higher levels of management.

The quality of the closure plan varies considerably, as might be expected for mines working independently on a new type of activity. A common flaw of many plans is that they hinge on the positive outcome of some risky assumption (for example, that ARD will not be a problem or will be self-remediating).

The closure plan usually identifies some past activity that the mine regrets (i.e. placement of a particular waste dump or improper disposal of waste rock that is creating acid rock drainage) but this is part of the learning experience as new criteria for mining are introduced.

To develop a plan, deficiencies in technical understanding are often identified and new tools are developed to aid in the closure plan. All mines reported that one of the fundamental things they needed to develop the closure plan was a good digitized topography of the disturbed and adjacent areas. This was a critical first step.

Most mines are using a basic GIS system to develop their mine plans including closure plans that contain several levels, each with different data. The GIS systems do not seem to be linked with databases for performance but instead are topographically and aerially based.

Mine closure planning usually highlights deficiencies in an understanding of the site hydrology. Sometimes climate stations are being installed and often stream flows are being monitoring. Usually a consultant is brought on board to work with existing data to come up with a closure hydrology system with much new data. As discussed later, closure practice tends to do a poor job on hydrology construction.

Surprisingly, closure plans generally do a poor job of identifying end land use and closure goals. Usually these activities are left as arm-waving exercises. In some cases, stakeholder consultation is included in the closure planning but is usually based on meetings with stakeholders before the closure plan is developed. It seems likely that the government and mining company will use the closure plan to take to stakeholders for their input into the second-generation closure plan.

Post-closure monitoring, unless for active maintenance, is usually poorly identified in closure planning.

Biological and ecological models are usually under development for some feature of the closure landscape (often a lake) and are usually featured prominently in plans.

Field demonstration and test sites are often developed as the closure plan is being developed to try out new ideas and demonstrate the effectiveness of other ideas.

- **Second generation closure plan**

No mines had developed second-generation closure plans except those in their post-closure period who were drafting final plans and blueprints for actual construction. It seems likely that the mines will develop a second generation closure plan as part of their next submission for re-permitting to the government, which is usually in response to a change in the mine limits or production rates. As mentioned above, mines should probably update their closure plans about every five years.

For those developing plans during their closure phase, there is ongoing negotiation with the government. In some ways, the government and the stakeholders have the upper hand in that they can demand expensive reclamation activities. In other ways, the mine is often on a tight time frame and restricted budget and so pushes closure planning through the government quickly.

Sometimes the second-generation closure plan contains additional technical information or learnings on specific items that were either identified in the conceptual closure plan or were ongoing when the conceptual closure plan was drafted.

- **Closure plans developed after closure (decommissioning plans)**

Since there are literally tens to hundreds of thousands of abandoned mines, most sites will only ever have a closure plan developed after closure.

A detailed closure plan is required at closure. These plans contain specific information about how to construct the closure landscape and decommission the facilities. In fact, this type of plan could be referred to as a decommissioning plan rather than a closure plan. It could have many of the same elements, but this is when actual decisions are made and agreed to. It needs to be based on the science and knowledge available at that time – there is little room for research or experimentation.

In many cases, the decommissioning plan calls for use of the mine's heavy equipment to finish the closure landscape. However, in most cases, a few months after closure, the mine management moves or sells off its heavy equipment and only a few small pieces of equipment are left for closure activities. As well, the budgets for closure are usually slashed and the timeframes for closure greatly extended.

- **As-built closure landscape**

Although few mines have progressed to the point of abandonment to the Crown, it would seem that as part of their application for abandonment an as-built plan of the site be provided to the government for approval. This would include:

- topographic plan of the site
- plan views showing soils, vegetation, wildlife habitat
- cross-sections showing material types
- signoff on geotechnical stability, dam safety issues, ARD or other chemical concerns
- plans for long-term maintenance (if any)
- bonding considerations
- hydrologic and groundwater water balances
- history of site performance
- copies of reports on technical details
- locations of monitoring sites (wells, etc.).

3.1.4 Closure path

To make closure planning a successful activity, mines and regulators are moving towards a closure path. A closure path is the orderly progression of activities that leads to the successful abandonment of the site back to the Crown. The closure plan is only one step (although a major one) in achieving successful closure.

Mines that are making the closure path successful use routine site wide monitoring (often yearly) backed up by a series of environmental audits. These audits cover the complete site and measure and document compliance and deviations from the closure plan. The audits can be done in several stages:

- Monthly audit by the site (one or two days each month).
- Yearly review by the company head office (a few days, mainly ensuring that the audits are done and that there are systems in place to catch various shortcomings)
- Independent external audit every five years.

Some companies are adopting IS 9001 or IS 14000 for these procedures although these systems are not always ideally suited. Sometimes too much effort is spent on meeting these external standards rather than focussing on doing good planning and reclamation. There is no one system that guarantees success.

3.1.5 Closure planning findings

- **General observations of closure planning**

Figure 3.1 shows the main profession/occupation of the main closure leader. At most sites, there is a single person who handles the day to day closure work as well as government submissions and closure plans. About a third are biologists and foresters, a third are physical scientists and engineers (civil and geotechnical engineers, geologists and geomorphologists), and a third are mining engineers or mine managers or foremen. There are also a few historians (who manage historical minesites) in this role. Consultants, usually the geotechnical or environmental consultants who have always worked for the mine, often aid or lead the preparation of closure planning documents for government submission.

It was noted that where a biologist is the lead person, the focus is on revegetation. Where physical scientists and engineers lead, there is a focus on physical stability and covering ARD dumps. Where mining engineers and managers take the lead, the focus is on material movement and regrading, mostly focussing on costs and schedules. The resulting landscape is a function of who is leading the reclamation effort. It is unclear the degree to which the major landscape issues dictate the type of closure expert or whether it is the type of closure expert dictates the major landscape issues.

There generally needs to be one person who leads closure planning activities. And although it is becoming recognized that closure planning is a multidisciplinary job, only at one mine was there a well-defined closure planning team. Effective closure planning needs to integrate efforts of different disciplines (namely planning, geotechnical, hydrological, groundwater, soils, vegetation, wildlife, and sometimes water treatment) more fully.

Closure planning is usually started at a mine to meet a regulatory requirement. Sometimes it is a requirement of owners or shareholders. It is likely to become a requirement of all mines that have publicly traded stock. Most mines have completed one closure plan and are scheduled to do another. Often mine plans and reclamation issues change enough every five years to make a new plan necessary.

Figure 3.2 shows a general picture of the reclamation and closure planning status for the mines. In summary, about a third of the sites visited were in active production and most of these had good reclamation plans or closure plans. About a third of the mines visited were in the closure or care and maintenance period had generally developed their first closure plan just before or just after operations ceased and almost all had a well thought-out closure plan. Ten sites were visited that classified as "new reclamation" meaning that they had been abandoned but were now receiving closure attention under abandoned mines remediation programs. These ten sites had either a reclamation or closure plan. Dormant, abandoned and historic sites had no closure plans and some had no reclamation.

In summary, it turns out that, due mostly to regulatory requirements, most active mines and those entering the closure period have well developed, first generation closure plans developed in the previous two to five years. Other sites had none.

- **What really happens with closure planning when a mine starts**

Most mines recognize that closure planning is worthwhile and that in most cases it's a regulatory requirement anyway. As a result, most mines starting up have a conceptual closure plan in place as part of their permitting process.

But mines are generally very focussed on more immediate matters of securing the necessary permits, gathering baseline information and, most importantly, mine planning and site preparation. Closure planning often highlights uncertainties or gaps in reclamation plans so mines are often less willing to put a lot of effort into closure planning activities during the initial stages of mine development. The managers believe they need to focus on getting the mine up and running first, and paying more attention on fixing any problems that arise later. They recognize that closure planning could identify problems that might delay the permitting process. No one wants to hear about mine closure as they are celebrating a mine opening.

This attitude towards closure planning in the early stages seems fairly pervasive in the industry. This attitude is unfortunate particularly since most key decisions that affect reclamation, closure and landscape performance – siting of pits, dumps, tailings ponds, their geometries, and methods of characterizing and handling materials – are made in the early days.

At the same time, it takes a lot of effort and fortitude to get a mine up and running, and time is always of the essence. If all the focus went into closure planning, the mine wouldn't get off the ground in the first place.

The key is to have the mine development team carry closure planning as a parallel activity, but closely integrated in the main mine planning activities. Research and development, and most especially site characterization, needs to start in the late exploration phase so it doesn't hold up the mine permitting and can offer good data and ideas in a timely manner. Closure planning needs to remain at a conceptual level since the plans change rapidly and radically during early development stages. And it needs to focus on the major concerns – potential showstoppers, correct handling of materials that could produce acid rock drainage or groundwater plumes, the major surface hydrology, overall configurations of waste dumps, and public consultation. The many minor details, often only of interest to the scientists, engineers and regulators involved in closure planning, truly need to be left until later.

Finding the fine line between conceptual and detailed information is challenging but critical. The use of an external panel with experienced people to guide these activities can help.

- **What really happens when a mine closes**

While mines usually have the best intentions of completing their reclamation and closure activities when production ceases, many things can happen at closure, most of which are unforeseen but follow a predictable pattern. Some mines are able to quickly adjust to closure activities (such as Island Copper), but many follow a less desirable path, as described below.

Generally, there is a rapid reduction in workforce at closure (see Figure 3.3). In real terms, a typical mine employs about 400 people at peak production. During closure activities, mines usually employ about ten percent of this workforce (about 40). After most of the reclamation is complete, one about one percent of the peak workforce remains to tie up loose ends or maintain the site and, after closure, two to four caretakers stay behind.

The closure period is very difficult for mine employees and contractors. Production usually ramps down in the later years. Closure usually happens suddenly, typically a few months sooner than planned, often due to a major accident which results from higher risks and lower maintenance being undertaken in the final stages of operation or sudden commodity price drops. Examples of mines experiencing sudden closure or changes include Granisle (caused by a storm / flood), Brenda (a pitslope failure) and Suncor (a bucketwheel collapse which ended bucketwheel mining). Also at this time, people are moving away, house values drop, and businesses go broke. There is always talk of re-opening the mine or selling it along with schemes for other businesses or industries. The community suffers a "de-multiplier" effect as the highest paid portion of its population moves away. If the town is small enough, economic collapse ensues.

The people left behind at the mine are often the people with the most seniority. A mine manager may be brought in to complete the work before retirement. The manager takes care of the bills, reports to home office and the government, and tours visitors. One or two other tradespeople take care of the electricity, pumping water, digging ditches, and maintaining the site. If there is a water treatment plant, a few people run it and monitor the site.

Oddly enough, closure is also a hard time for reclamation and closure activities. There is a pattern of activity at closure which is both common and troublesome.

- As mentioned above, closure for a mine looms for some time, then usually happens suddenly. One morning, the mine is no longer in operation.
- Most of the staff is laid off and, as a result, a tremendous amount of information and site experience is lost overnight. This loss of information and experience can be referred to as the "closure infogap." The filing systems at mines is often poor and information is often thrown away as offices are shut down. Mines often mistakenly believe that consultants and government agencies maintain good records of their sites, reports, and their submissions.
- There is often a major change to the closure plan at the time of actual closure. Big equipment that was to be left behind for closure activities is sold or moved to a nearby operating mine.

Cash flow ceases, the warehouse and local supply shops close, and people who kept the mine running smoothly are gone.

- There is a large area left to be reclaimed, usually from 50 to 80 percent of the entire site. Usually many activities – resloping, crust management for soft tailings areas, road decommissioning – remain to be done before even the purely reclamation activities can take place, and the task can be daunting.
- Mine closure activities and reclamation activities often come to a halt.
- The mine is no longer profitable so reclamation and other expenses can no longer be written off against profits or royalties and the mine pays the full amount of these activities (often doubling or tripling the effective costs).
- The site goes into dormancy. A few pumping stations and pipelines are set up to pump water around the site, often to the mined-out pit. Many of the buildings and shops are removed. Equipment that cannot be sold is lined up and mothballed or simply left there. A few "No trespassing" signs go up and the site is barricaded.
- The site remains in dormancy until a new buyer is found or until the mining company decides to continue closure and reclamation activities. Sometimes, small amounts of reclamation activities are done each year to satisfy regulators that progress is being made. This reclamation often starts with the easiest work or, sometimes, economics determines the work such as capping dumps to limit air and water percolation in order to minimize water treatment costs.

For all these reasons, a broader "closure gap" exists which can include gaps in information, cash flow, equipment, materials and desire. As well, the mine may be influenced by other factors. For example, the mining company may:

- hope to sell the property for its remaining reserves (or reopen the mine at a future date) and doesn't want to incur large closure costs
- in the absence of regulatory pressure, want to extend the closure activities over years based on discount cash flow economics
- hope for a change in regulatory heart which will allow it to do less reclamation than previously negotiated
- hope for a new technology to reduce costs
- feel the benefits of reclamation do not justify the high costs
- be busy reclaiming and closing other sites and wish to postpone closure
- be actively developing closure plans for the site
- hope to avoid having to reclaim the site altogether
- leave the site dormant due to legal battles.

The result is that progressive reclamation is a necessity, if for nothing more than to reduce the overwhelming cost of closure at closure. Some U.S. jurisdictions have strict regulations to prevent extended dormancy periods, but these seem rather inflexible. The solution is likely to have mines submit closure plans, schedules and costs, and to steward to the government regulators that the work is being done. Failure to meet commitments should result in a forfeit of the bond or being billed for government reclamation of the work.

Re-mining or reprocessing of tailings deserves special comment. Some gold tailings in South Africa, for example, has already occurred several times and can be expected to occur several times more. Reclamation of these tailings sites to natural ecosystems that would have to be stripped away for re-mining would make little sense. Here the closure plan should show stabilization of the tailings (to limit erosion and dusting) in such away that the resource is not sterilized. The mine should be accountable for this as a closure plan.

- **What mines did well**

People at the mines were asked what they did that really benefited the closure planning process. Generally, mines:

- got a better handle on the baseline data (mainly biological) than the government or stakeholders so that concerns could be addressed immediately and with confidence
- worked closely with university and government consultants to develop defensible scientific research
- worked closely with stakeholders to develop end land use plans
- established good public relations including tours, photo sites, etc.
- made a closure plan
- did more than was required by the regulators
- divided the site into operational units that could be turned over in chunks
- worked closely with employees to find them new jobs and worked closely with the town to manage the transition
- used the opportunity to evaluate tailings disposal methods and make a change
- have good historical records of background stream metal concentration
- focus on and monitor ingress of volunteer vegetation
- used the results of the closure planning process to direct and focus research on key elements
- avoided disturbing rare wetlands which would be expensive to recreate
- establish an international review board for closure activities
- establish an insurance fund against poor landscape performance
- integrate closure planning with environmental monitoring through the use of GIS
- pay attention to aesthetics
- form an interdisciplinary team
- create a system where equal amounts of land are disturbed, reclaimed and, in particular, certified every year.

- **What mines would do differently**

People at the mines were asked what they would have done differently given a better closure plan. Mines would:

- do a better job of identifying hazardous conditions before mining started – especially assessing likelihood of acid rock drainage and the best control methods
- avoid using ARD waste rock as starter dykes for tailings dams
- ensure better segregation of wastes into hazardous and non hazardous stockpiles
- ensure better collection and maintenance of historical data and better baseline data
- continue subaqueous depositing of acid generating tailings and waste rock

- not have mined the site at all (closure costs were greater than the profits)
- not have purchased a dormant site (closure costs were greater than any benefits from resale or new mining)
- not have placed wastes (rock and tailings) on the floodplain
- have located the company town farther away
- have zoned the sites to make few areas maintenance intensive
- have left holes in building foundations to make loading explosives for blasting easier
- got more land certified earlier to establish precedence and show ongoing transfer.

- **General suggestions**

Mines were asked what the number one suggestion for closure development would be.

- have senior management commitment before starting
- get good topographic detail for the mine and adjacent areas for base maps
- identify all the issues for all the waste materials
- have a plan in mind before approaching stakeholders and regulators
- capitalize and amortize closure expenses, and get them in the budget
- reclaim as you go, and finish the major work as soon as possible after closure
- make sure that key assumptions are supportable and accurate
- negotiate with stakeholders and government well before closure
- stay at the conceptual level given that plans will change
- plan for a maintenance free landscape as much as possible
- involve government and university researchers
- establish regular environmental audits
- don't plant grass where you want trees.

- **Key features overlooked**

Although most mines are doing a good job of closure planning and reclamation, there are recurring themes to areas that are overlooked or ignored.

- Most mines have not established formal closure goals. There are many unstated goals (usually goals of the main closure person).
- Most mines have not addressed the methodology of abandonment. Most have avoided discussing maintenance, bonding, and long-term liability, and long-term dam safety considerations have not been addressed.
- In general, long-term erosion has not been considered. If designed, most closure facilities are designed for 100 to 200 year flood or seismic events with no consideration of the effects of an event which exceeded design. Weathering leading to slope instability is also a concern, especially for waste dumps constructed of soft rocks at their angle of repose.
- The most major physical issue overlooked is the site hydrology. The hydrology at most sites is poorly understood, modelled and constructed. Often armouring of hydrological features is inadequate. Many features are "semi designed" which means they were constructed without design or by non-technical people.
- Bonding levels or the need for bonding remains a contentious issue.
- Risk assessment, independent audit and stakeholder involvement are seldom part of the closure planning process.

- Too often, a key element of the closure plan to ensure good landscape performance is simply overlooked – sometimes because, to consider it in the plan would cause such a great cost or change, it is almost unthinkable. Mines have to be careful to avoid ignoring critical elements.

Overall, mines are doing a good job of closure planning in general, but the effectiveness of the plans and closure planning process (the closure path) could be significantly improved from learning from the experiences of others, and following a more formal process.

3.2 Closure goals

As described in the previous section, setting goals is a step in closure planning and reclamation that mines generally handle poorly. This section details and summarizes the goals for reclamation and landscape performance based on discussions with the mine reclamation personnel on the tours.

3.2.1 A compendium of goals

Overwhelmingly, just about all mines have a strong focus on creating stable landscape, greening it up with a vegetative cover, and meeting or exceeding reclamation and environmental regulations, and solving problems as they arise. They feel a strong corporate commitment to make the land useful again.

Table 3.1 presents a brief summary of the closure goals, challenges and novel concepts learned during the visits to the mines. These are described in greater detail in Appendices A, B and C and discussed below. Figure 3.4 provides a graphical representation of the number one closure issue at each mine. The number one concern is split among five main categories: costs, vegetation performance, physical stability (geotechnical and erosional), acid rock drainage, and human safety (radiological, physical safety and building removal). At sites with ARD and radiological concerns, closure planning and reclamation has a higher profile than sites where offsite and human safety concerns are less prevalent.

Figures 3.5 and 3.6 summarize primary and secondary closure goals graphically. Most mines only have a couple of stated goals, which are usually vague or poorly defined. These were taken as primary goals. Many mines, however, have numerous secondary goals, often chosen by the reclamation leader.

Most mines list removal of physical hazards (gullying, geotechnical instability, dusting and infrastructure) as a primary goal. Returning the land to the original owner with thriving ecosystems are common land use goals. Typical goals that benefit the mine include enhancing the visual appeal of the landscape, satisfying stakeholders, enhancing public relations, and minimizing long term maintenance. Regulatory approval, mainly in the areas of vegetation, water quality and bioproductivity, were among the most often stated goals. Where outside stakeholders had a dominant influence on reclamation and closure, they were often seeking to create employment for local people after mine closure.

Specifically, the top 11 goals reported by at least 40 percent of the mines were:

- return of land
- regulatory approval
- enhance visual aspects
- avoid gullying
- avoid physical hazards to users
- encourage wildlife
- meet vegetation regulations
- meet water quality regulations
- geotechnical stability
- removal physical hazards
- removal of infrastructure.

Mines more advanced in their closure plans recognized that the reduction in liability, and approval and support of stakeholders and regulators were the overriding goals of mine reclamation and closure. Most mines were focussed on the more technical issues, reclaiming for the sake of reclamation.

3.2.2 Discussion

Mines have a problem with setting and fulfilling goals. Mines recognize that they have a commitment to reclaim the land and that they are accountable for fulfilling regulations to this end. They also recognize a broader duty to society to return the land to a state where it is useful – usually to rejoin some kind of natural ecosystem. Usually greening up the landscape is a practical substitute for all of the above.

But few people directly involved with reclamation understand the broader corporate perspective and their duty to shareholders – they are employed and charged with reducing the liability of the mining company and, in a nutshell, increasing the shareholder wealth. Their job is to fulfil the commitment made to regulators by reclaiming the land, thereby reducing outstanding liability. This necessitates justifying any expenditures that are beyond the minimum required to meet the commitments.

Progressive reclamation, in addition to being a requirement of most regulatory agencies, allows mines to reduce liability in a progressive manner. There is a cost to carrying the liability of unreclaimed land, so progressive reclamation also reduces the costs to a mine.

Reclamation can have ancillary benefits to the mine. Going above and beyond the minimum requirements can have public relations benefits which may be difficult to determine but can be important to share value and long-term viability of the mine. These efforts can be critically important when it comes time to renew permits or open new mines. Goals to go above and beyond minimum requirements should be tracked separately from goals related to minimum requirements. They should also be subject to a cost-benefit analysis, even if the benefits are difficult to quantify.

More than a few goals at most mines are usually a result of pet projects of the reclamation experts. Examples would be rock piles for small mammals, providing feed for elk, and research plots for certain kinds of trees. These kinds of goals are usually only thought to be worthwhile by the individuals involved. While it is important to allow employees to experiment and make their own mark on reclamation projects, these goals and these activities should be carefully managed.

Professionals working in mine reclamation may feel a larger duty to society than to the mine or regulators, and may feel the need to exceed regulations in the best interests of society. Likely, this is seldom thought about in terms of specific duty but rather doing what is 'right,' which will usually also be in the best interest of the mine.

In many cases, the regulatory requirements are a bare minimum for reclamation and do not address long-term performance or risk. In general, there is no direct assessment of risk and building landscapes to minimum requirements often meets the fragile-under-extreme (or even modestly large) events. Mines will exceed the minimum to build more robust landscapes.

In all but some of the U.S. mines that operate under very prescriptive regulations, mines' goals exceed regulatory requirements. Part of this relates to the desire to satisfy the above hopes for increased public support, pet projects and building in some robustness. However, ways in which the mines choose to exceed regulations are sporadic and sometimes counterproductive.

In particular, mines often agree to unrealistic or even unachievable goals during the permitting process. In the initial permitting process, there are uncertainties about future environmental performance and people are acutely aware of the drastic disturbance the mine will cause. Mines are very keen to get their permit and, having already committed the funds, delays in starting production are extremely costly – usually tens to even hundreds of millions of opportunity cost for each year of delay. The result is often a "permit at any cost" mentality. Agreements to unrealistic goals may be made with both regulators and key stakeholders. Often the agreements are made by mine management without or against the recommendations of the reclamation specialists or consultants.

During the environmental impact assessment (EIA) phase, mines usually agree to mitigate almost all damage caused by mining. Regulators use this assessment to evaluate the project based on the tradeoffs of jobs and economic returns to society versus residual environmental affects. This phase is the source of many goals or agreements that mines make to mitigate their impact. Some mines view these goals as "what might be possible" but most regulators and stakeholders consider them to be a contract – they have been used to evaluate whether mining is advisable. During this time of permitting, there is a lot of optimism that spills over into the goal setting period. Table 3.2 outlines examples of unrealistic or high-risk goals.

In theory, as new information becomes available (especially unexpected poor performance, failure mechanisms, or that goals are unlikely to be met), it should trigger a review, update, or creation of a new EIA to see if continued mining is still in the best interest of society. In practice, this level of scrutiny is rare.

From a purely economic viewpoint, agreeing to expensive goals may be worthwhile. The costs of meeting these goals at a future date may be less than the cost of a delay. Quite often, reclamation specialists are left attempting to fulfil the agreed upon goals, often with little management support or money. Mines often argue that the costs of fulfilling these goals are unreasonable, and ask to be excused from them. Or worse, year after year goes by, with the mine promising to meet the goals at some unspecified time in the future.

Sometimes, the individual goals are not unreasonable, but there are so many goals, fulfilling them all is difficult or impossible. Mines are in the habit of promising all things to all people. If one were to add up all the environmental regulations (which can include requirements from up to two dozen different acts, guidelines, agreements, and policy) there can be a hundred or more goals for reclamation and the landscape. The regulations, which are essentially goals for the mine, are imported from other fields such as forestry, fish and wildlife, agriculture, landfills, water treatment. As a result, they don't reflect the nature of mining – disturbance of large areas, creation of vast wealth, dealing with large volumes of homogeneous, metaliferous wastes, low profit margins. The ability of mines to satisfy all of these goals, everywhere on site, with an open-ended timeframe is clearly impossible. Regulators are clearly selective in the application of these regulations.

On top of all this, goals are usually poorly defined and success is difficult to measure.

- How long do the goals have to be met – during operation, pre-certification monitoring, for 100 years, in perpetuity?
- Do some goals have precedence over others?
- Do the goals have to be met at all times – during extreme events such as fire, drought or floods?
- Must goals be met at all reclaimed locations – highly mineralized groundwater in dumps, seeping from toes, within the disturbed footprint, on-lease, off-lease?

Attempts to predefine the answers to these questions usually leads to more complicated and prescriptive regulations and can be counterproductive. Attempts to define all of these questions clearly yields even greater complexity and over-regulation. It simply becomes unworkable. Clearly a better, largely performance-based approach is preferable along with a more rational set of goals.

Making mines even more uncomfortable, most jurisdictions reserve the right to apply new legislation to mines. Areas that are reclaimed (or sometimes all the areas that are disturbed) are exempted from these changes but this is seldom set out clearly. These jurisdictions reserve the right to apply new legislation retroactively, even after the sites are reclaimed, certified, and returned to the state. Recent "polluter pays" legislation is a good example of retroactive liability.

What became apparent in the mine tours is that mines have unlimited liability for their activities and moving regulatory goal posts is one of their greatest concerns. Most mines believe they will discharge their liability upon final reclamation, but some recognize they are essentially liable forever.

This vast exposure to liability is especially troublesome to large mining companies that operate numerous mines in many jurisdictions. With the start of every mine, they accumulate liability and it is common to use the profits from operating mines to pay for the reclamation of mines in the closure phase. Depending upon how one evaluates the accumulated liability, an otherwise profitable international mining company can find it impossible to raise new capital for new mines and many of the existing old mines will go into dormancy. Where financial assurance for reclamation, closure and long-term maintenance is an issue, mines will usually offer corporate assurances based on assets, including operating mines. Some mining companies will not have enough assets to satisfy retroactive bonding requirements for all of their mines.

Concern about agreements to meet unreasonable goals is not only an academic one but can have grave consequences for a mining company due to the exposure to liability. Both mines and regulators need to overhaul their framework of goal setting and methods of achieving these goals. In general today, if mines are showing an honest effort to reclaim their minesites, making them safe and useful, regulators are usually reasonable and only apply regulations that are reasonable and important.

But the crunch comes when closure is reached and the landscapes are reclaimed. There is a nearly complete lack of land being turned over to willing custodians – almost no land has received reclamation certification or been turned back to the state. The reason is there are too many outstanding goals that remain unfulfilled and, probably more of a concern, there is a lack of reliability that the landscapes will continue to perform as intended in the future. Regulators are concerned about being accountable about approving reclamation that may not meet all requirements and may fail in the future. Mines are concerned about ongoing liability that includes liability for redisturbance of the site by others, and are unwilling to give control of the land back to the Crown.

The result is that the mining industry is failing to fulfil its promise of temporary use of the land – the land remains under control of the mines essentially forever. And the regulators are failing to fulfil their role of signing off on good reclamation. The overall result is a loss for society – shareholders are affected by owning companies that are exposed to unlimited liability, the land is not being returned to the government for new uses, and mining companies are moving operations (and the economic benefits) to where the regulatory environment is more favourable.

One solution to this stand-off is to adapt a new philosophy of reclamation and closure regulation that is based on landscape performance and regulated with a minimum number of clearly defined performance goals by regulators willing to enforce and sign off when completed. There are both economic and environmental benefits to a new approach.

Landscape engineering, offers guidance on setting goals, methods to achieve them, and methods to regulate this approach. Along with closure planning and design methods, goal setting and performance criteria are central to this new discipline. A major shift in philosophy to one of designing for overall landscape performance and agreement to use specific design and construction methods (rather than agreement to specific long-term performance or prescriptive methods) is a way to setting achievable goals.

3.3 Landscape design and construction

Aspects of landscape design can be categorized several ways. A particularly useful way is to look at the various technical specialities that need to be involved in generating landscape designs: geotechnical, surface-water hydrology, groundwater, soils, vegetation, wildlife, traditional environmental knowledge (TEK) and those regarding human health and safety.

3.3.1 Geotechnical

Geotechnical aspects of mine closure are generally well handled, mainly because the need for formal geotechnical design of dumps and dams is an accepted practice (an outcome of the Aberfan disaster of 1966). Geotechnical aspects include slope stability, subsidence, undermining, soft tailings stabilization, and dam safety.

Most of the sites visited have good slope stability. There are occasionally small slumps that do not impact overall landscape performance but these are limited. Some sites, especially those along rivers or with large in-pit lakes, may be at risk to long-term instability due to toe erosion of slopes. Others may be at risk to landslides due to increases in closure water tables. About ten percent of the sites had some slope instability, only a few of these sites is the instability a problem for landscape performance.

Subsidence, especially differential subsidence, is a certainty for thick fills (such as tailings fills, dumps, and soft tailings). The two greatest impacts are for structures founded on these substrates (including buildings, roads, pipelines, powerlines and ditches) and for ponding of water. Other than changing soil moisture conditions, subsidence was not seen to be great or contributing to degraded landscape performance. Only a few sites have problems with subsidence.

Stabilization against cave-ins from undermining is common practice in underground coal mining in populous regions. At the sites visited, concrete plugs and grouting of near-surface voids seem to progress fairly well and performance generally acceptable, but occasional cave-ins or subsidence generally require long-term financial assurance or insurance. The literature has a lot of examples of undermining disaster sites and perhaps these cases were under-represented in the present survey. Reclaiming undermined areas, especially where mining was close to the surface, presents special challenges and needs to be treated carefully.

Dam safety is a long-term issue at many mines. Recognition of the need for long-term monitoring of tailings facilities in particular comes as a surprise to many mines. Recent changes to dam safety legislation to include tailing dams more formally do not recognize the nature of long-term dams, particularly those that have no reservoirs but contain potentially liquefiable or very soft materials. The issue is not necessarily the long-term performance but recognition of the need for annual inspections and periodic maintenance.

Soft tailings stabilization and reclamation presents a special challenge to mines. It usually comes as a surprise at closure. Stabilization needs to be done with small and specialized equipment, and often costs 20 to 30 times that of normal reclamation. Interestingly, it can cost more to reclaim a tailings pond than the cost to build it. Most mines are satisfied with stabilizing and greening-up these sites. Water capping is often employed successfully. The performance, once reclaimed, seems to be reasonably good but the reclamation itself is difficult. Avoiding or minimizing the cost of soft tailings is perhaps one of the goals of good early closure planning. Long-term subsidence of soft tailing deposits remains an issue.

In general, other than considerations for long-term term changes, geotechnical aspects of landscape design are well handled. The method by which landforms are designed, constructed, licensed, and monitored to meet geotechnical goals can serve as a model for other specialities involved in landscape design. Some improvement of planning for soft tailings stabilization would be beneficial. Economic and regulatory methods to deal with long-term dam safety issues and risks of cave-ins from undermining would also be helpful.

3.3.2 Surface water hydrology and topography

There's no doubt that hydrology is the number one landscape issue for mines across North America. The reasons for its importance are that it is fundamental to the physical stability of the landscape (upon which the soils and vegetation and ultimately end land use depends); it is a mechanism for unzippering of the rest of the landscape; and flow water is one of the major vehicles for causing significant off-site impacts.

The reason for the near lack of surface water hydrology design for closure at most minesites is not clear. Based on the experience described below, the new discipline of landscape engineering will need to have surface water hydrology as a major element.

Re-establishing the hydrology is a major issue for mines and often costs between 10 and 20 percent of the total closure costs. Almost half the sites visited had no formal design for slope drainage or creeks/rivers. At about a quarter of the mines, the streams are 'semi-designed' which is short for field fitting without engineering. If they are designed, most streams are only built for 100 to 200 year events with no consideration for exceedence. Beaver dams or other blockages (slumps, log jams, siltation, ice, road crossings) are not considered at any mines visited. When a formal hydrological design is done, usually the armouring is found to be too costly for the mine so they only build the cross-section but leave it unarmoured or armoured with small cobbles. Many mines ignore the regional hydrology in their reclamation and allow creeks and rivers to cut into wastes over time.

Somehow, mines have move away from actually designing overland flow into landform designs. The industry assumes sheet flow, but doesn't do the calculations or design. This is particularly problematic for tailings slopes, especially where the grain size is fine enough to favour runoff over infiltration or percolation. As a result, fine-grained tailings slopes are nearly unreclaimable. Waste dump slopes would also benefit from hydrologic design.

Figure 3.7 shows the typical design slope angles for tailings dams and dumps. Angles of 2H:1V are common in mountain coal mines, angles of 3H:1V to 5H:1V are common in other areas with good foundation conditions, and flatter slopes (even to 26H:1V) are common in oil sands areas that have extremely weak clay-shale foundation conditions. The steeper slope angles are usually prescribed and based generally on vegetative and erosional concerns. The flatter range of slope angles is usually driven by geotechnical stability considerations.

Almost all mines, with the exception of some resloped coal spoils in some areas, use terraces on their dumps. They are usually spaced at 50 to 100 metre intervals (slope lengths). Surface downdrains are uncommon and sheetflow, where considered, dominates. In particular, U.S. mines pay lip-service to overland flows as they are required by law. Few Canadian mines consider hydrology at all in their reclamation. Streams, if designed at all, usually are roughed in without engineering design.

Terraces, one of the greatest improvements to dump design 20 to 30 years ago, may not be as ideal as they tend to concentrate flow and contribute to erosion[9]. But terraces do have their benefits and a limited number need to be carefully designed into the landscape.

Only about a quarter of mines design their waterways (creeks and rivers and slope runoff). Figure 3.8 shows typical flood design return periods for design of creeks. The design for operational periods is usually one of 10, 100 or 200 years. The design for long-term periods is usually 100 or 200 year return periods. Few mines could answer who would take care of damage in the event of exceedence of design events.

About half of the mines have high infiltration rates (especially into coarse waste rock dumps). Most ARD sites are using engineered covers to limit infiltration or to limit deep percolation. A few mines have created coarse permeable zones to enhance infiltration to limit surface erosion.

About a quarter of mines visited are at risk to beaver dams blocking a key streams or spillway, flooding large areas or causing some kind of overtopping failure. Only one of the mines considers beaver activity in the design of creeks and streams. About six mines with occasional beaver problems simply periodically shot the beavers.

The downstream (outer) slopes of tailings dams constructed with mine tailings showed poor performance – poor vegetation establishment and growth, and high levels of gully erosion. Mines with cyclone tailings showed only slightly better performance.

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[9] Often the newest in technology (such as terraces, constructing to approximate original contours, contour ploughing) are found ten years later to not be as successful as originally hoped. Today's leading technologies such as passive water treatment wetlands and dump infiltration covers may suffer a similar fate (useful, but not ideal). Future efforts, such as those suggested here and in new technologies in landscape engineering, seem very promising, but given the law of averages and historical experience, may not live up to all expectations. The strategy should be to employ these new technologies with care, and closely monitor the landscape performance, adjusting practices as necessary (a principle of adaptive management).

In the U.S., many mines are subject to regulations that prescribe maximum slope lengths, dimensions of catchment berms and slope angles so overland flow is partially, but imperfectly (and perhaps blindly) considered at these mines. In Canada, few dumps or tailings dykes receive attention to detail with regard to design to limit erosion.

The hydrology of end-of-pit lakes also proves to be problematic to the point where the pit filling is nearly unpredictable (see Table 4.2). Most pits fill must faster than predicted (by a factor of two to five). Others stabilize at water levels that are too high or two low, greatly affecting the amount of littoral zone and, hence, the end land use and recreational potential of the lake. Almost all end-of-pit lakes (10 of 12 visited[10]) showed performance that was significantly different than predicted. Here are some examples:

- Brenda Mine was expected to fill in 25 years but was on track for filling in six years.
- Island Copper filled with seawater faster than expected due to erosion and widening of the inlet channel.
- One of Highland Valley Copper pit's filled to a much higher level than expected, necessitating a change in end land use and construction of a spillway.
- Tent Mountain's main pit stabilized at a lake level much lower than the preconstructed outlet.

About a quarter of the mines visited are experimenting with geomorphic approaches (designing slopes or creeks based on observations of nearby natural terrain or designs) that recognize the geomorphic evolution of the landscape (erosion, gullying, and subsidence). Most of these are in a very limited, informal, or experimental way.

Landform grading is being practised or attempted at a few mines, but not systematically. It has been applied successfully for large residential developments in California[11] and elsewhere for the past 20 years and many of these projects are large even by mining standards.

Landform grading breaks the slopes into distinct watersheds with their own drainages so there is virtually no erosion or maintenance. For mining, the most important features landform grading offers are stability and diversity although in most cases it is driven by aesthetics (see Table 3.6).

Mines that are employing landform grading are generally doing so in the absence of engineering design. This has been successful because of the typically small catchment areas and the high infiltration rates on waste-rock dumps. A more engineered approach will be required to ensure good long-term performance and, for larger areas, more erodible slopes. Mines achieve high public relations value from this effort and it is starting to become a requirement of stakeholders and regulators. The days of long linear and planar slopes and constant elevation ridgelines are numbered.[12]

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[10] The only two pits that matched predicted performance (Granisle and Bell mines) were on small islands with almost no watershed areas leading to the mined-out pits.

[11] For more information on landform grading, see Hoffman, 1977; McKenna, 1999; McKenna, 1999; Schor, 1995; Schor, 1980; Schor, 1993.

3.3.3 Groundwater

Groundwater and groundwater quality is a problem for many mines, partly due to vagaries in goals and partly due to uncertainty in methods, especially when coupled with uncertainties in mine planning and execution. That mines are located in highly mineralized areas and the mining activity exposes the soils and rocks to solute movement means that movement of metals and other ions in groundwater is generally inevitable.

The on-site groundwater is seldom viewed as an issue. Pore-water within tailings structures and waste rock dumps is usually poor, especially for metal mines. This seems to be tacitly accepted, perhaps because there are no reasonable alternatives.

The point of compliance for groundwater quality monitoring is usually a lease boundary, sometimes a disturbance boundary. Sometimes it is acceptable to show say 1000 years before a plume leaves the lease. Groundwater travel time predictions are however notoriously inaccurate, and plumes usually travel much faster (often by orders of magnitude) than predicted, often due to fissures or other forms of secondary permeability.

There are occasional problems, particularly with coalmines, which can physically remove aquifers relied upon for local drinking water. Drilling new wells or trucking in water is often required as a replacement.

The framework for satisfactory groundwater performance needs to be made much clearer during the initial closure planning and permitting stages for a mine. Remediation is very expensive and often not practical.

About ten percent of mines visited reported concerns with groundwater. A larger number ignored or even avoided determining effects of groundwater. Many have monitoring programs, but without a clear idea of what should happen if a plume were detected. Though well regulated elsewhere, groundwater remains a concern for landscape performance of mines.

3.3.4 Soils

Few mines have soil scientists involve in the design or placement of their cover soils, even though having good soils is perhaps the single most important issue for mine reclamation. Generally a few trial plots are used to assure reasonable growth of agronomic species – if performance is acceptable, this uniform thickness becomes the standard for the site (usually independent of slope, aspect, substrate, vegetation or land use). Even with these shortcomings, based on the apparently successful vegetation in most areas, most soils are performing adequately.

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[12] While this is more immediately true for dumps, dams and tailings dams may be longer in following.

Most mine reclamation requires placement of some thickness of coversoil over mine wastes, usually as a combined barrier or cover and as a vegetative growing medium. Many of the minesites had no cover soils and used either direct seeding techniques or simply no reclamation instead. For those mines with coversoil requirements, the thicknesses of coversoil ranged from a few centimetres to a couple of metres thickness. Thickness of 30, 50 and 100 centimetres were common, with greater depths reserved for problem substrates. Along with regrading, coversoil placement is usually the greatest reclamation cost. See Figure 3.9 for more information on coversoil thickness.

In general, placing the soils is largely a mine-planning task and mines are generally having little difficulty in meeting the regulations.

One of the main roles of soil in mine reclamation is to form a good growing medium so vegetation can help to prevent or limit erosion. This approach is usually successful, except where water is concentrated and the vegetative cover and cover soils are eroded, exposing the substrates below.

The mining industry, with notable exception, seems to be moving away from extensive soil capping. Direct seeding of mine wastes is becoming more common, particularly for soft rock mines and for tailings sand. Often the short term performance of waste rock dumps as soils is improved by the presence of nitrates (a fertilizer) left over from blasting. Soils will develop on their own but it will take hundreds or thousands of years to develop good soils. In some cases, the dumps can be zoned to promote direct seeding.

Design of new soils by qualified professionals is an important element of landscape engineering. It is also an important element of reclamation as it forms the basis of the vegetation, ecology and wildlife at the site.

3.3.5 Vegetation

Revegetation is the most advanced area of mine reclamation. It's becoming a highly developed science and the vegetation is performing well. Most stakeholders are mostly concerned about having sites that have good, self-sustaining vegetation. For most people, lush greenery is the main indicator of good landscape performance.

In terms of revegetation, about a quarter of the mines are doing some level of direct seeding of waste materials (from 10 to 100 percent of area). About three quarters of mines are using agronomic species for reclamation, and about one quarter are using native species. Three quarters of the mines are seeing some natural invasion of species, and about one third are seeing a lot. Very few monitor for invasion.

Almost all the mines visited focus on vegetation – mostly establishing grasses and legumes and a few work on establishing trees. Only a couple mines focus on ecosystems rather than just vegetation. But at the same time, about a quarter of the mines saw their vegetative efforts as a way to way to mitigate the disturbance to a point where nature will take over. Most mines are hesitant to plant trees, arguing that they are costly and will invade. Island planting schemes are used in some areas. Few mines monitor the influx of volunteer species into reclaimed areas, but where it occurs, most reclamation specialists take this as a positive sign of good performance.

Often, the major role of vegetation is to limit erosion on slopes and plateaus. With the exception of some of the desert mines, vegetation seems to be meeting this goal.

Unsatisfied with existing good performance, regulators are moving towards restricting choices of reclamation species to native ones and requiring patch-like mosaics of plantings to produce more sustainable and diverse vegetation and wildlife habitats. Soil development and ecology is becoming a focus area. Part of the move into these areas likely reflects the fact that existing revegetation practice, although very successful, may not meet all the future land use and sustainability goals.

For example, there is wider recognition that traditional measures such as productivity reflect management inputs (irrigation, fertilizer, etc.). As a result, there is a move toward a more land-capability approach that focuses more on the science of providing the right kind of soil rather than measuring tonnes / hectare of crop or forest production. This is especially true in Alberta.

Direct seeding of mine wastes is a major topic. Mines are often required to cap their mine wastes with soil but many are questioning this requirement and are demonstrating that direct seeding of mines wastes is advantageous and more economical than bringing in capping material. Successful direct seeding can result in a reduction of reclamation costs of 30 to 90 percent.

Revegetation typically costs about $2000 per hectare. Resloping often costs about the same again. Capping with 0.5 to 1.0 metre of reclamation material typically costs $10,000 to $30,000 per hectare. Successful elimination of the capping material can dramatically reduce reclamation costs. In some cases, trees planted directly into mine spoil performs better than those planted into capped spoils.

There is a backlash against trying to use native species and planting trees because:
- there is good success with agronomic species
- trees are more difficult to grow, slow to grow, and are more expensive
- deciduous trees work better than conifers
- it is costly to plant trees that may not grow
- better short term stability is achieved with grasses
- grasses are better at reducing infiltration and provide more protection against overland flow erosion

Many mines avoid tree planting and are taking their risks with the regulators and stakeholders.

Regulators often prefer native species for revegetation (even restricting seed collection to within certain distances and elevations of sites) because:
- native species are better adapted to local soil, climate, and vegetative conditions and tolerant of local insects and blights

- local wildlife are adapted to native vegetation species
- concerns remain about the introduction of non-native species into native ecosystems
- there is a desire to quickly re-establish local ecosystems similar to those that existed prior to mining
- there are re-establishments of land use (forestry, traditional land use) prior to mining by using similar species.

A less emotive and more practical approach is needed with respect to native and non-native vegetation. Most would agree on the benefits of using native species for the majority of reclamation work, especially as more native seed and seedlings become available. For some smaller areas, such as grassed waterways, non-native vegetation may make more sense. More research into the use of nursecrops (native or non-native), soil formation, and natural vegetation succession would be beneficial.

In summary, revegetation is generally well handled. Even if poorly handled, provided the soils are reasonably good, nature finds a way to revegetate sites. In that the performance is good and many of the reclamation specialists and regulators are biologists, there is a lot of innovation going on and expectations for the vegetation are high.

Most stakeholders view having a good, lush vegetative cover a major indicator of good landscape performance and so it deserves a lot of attention.

3.3.6 Wildlife

Wildlife is an issue at most mines – there is a general benevolence on the part of environmental staff towards wildlife, particularly mammals and large game mammals. But mines have little guidance in how to design their landscape to create wildlife habitat.

About 20 percent of mines are designing at least some areas of their landscapes to support wildlife. Some through selection of initial species planted others by providing feed, building of rock piles for small mammals or microtopography to support wildlife.

Only a couple mines are presently doing integrated wildlife plans for their sites, though more are exploring design and field methods.
There is quite a lot of interest in what amounts to temporary measures for wildlife habitat enhancement, including brushpiles, snags (standing dead trees/logs), birdhouses, revegetation using alfalfa and grasses, and even bringing in bales of feed in the winter. While there is often a tangible public relations benefit from such activities, these measures are temporary and, to make a real difference to wildlife levels at the site, would need to be much more numerous in the final landscape. So in terms of long-term landscape performance, most of these have limited value.

Wildlife habitat is most greatly influenced by vegetation, and some mines are considering planting in varying ecosite patch sizes of one to 10 hectares. To a lesser extent, these plantings are a temporary measure. Long-term diversity is only marginally correlated to initial planting and comes from a diversity of soils, substrates and topography. Long-term wildlife habitat is thus most greatly enhanced by creating diversity of landforms, topography and soils. This aspect of wildlife habitat is in its infancy.

It is interesting to note that wildlife often move to minesites. The fences help to keep out hunters, poachers and sometimes other shy predators, and the workers often provide food for the wildlife. The result is that reclaimed mine areas often have abnormally high levels of wildlife. It is common for mines to feature this wildlife in their environmental brochures because next to having lush vegetation, the presence of wildlife is a major indicator of good landscape performance to many stakeholders.

3.3.7 Human health and safety

Just about all mines see the need to protect human health and safety. Efforts to this end generally focus on removal of equipment, buildings and infrastructure, removal of barrels and chemical hazards, and protection for underground openings.

In general this is well handled, and most mines sites create conditions that are likely safer for humans than the surrounding landscapes. Sometimes, things are taken to extreme – for example, where mines go to great length to buttress highwalls and backfill mine pits to this end.

Creating landscape that provides for human health and safety should be the highest goal.

3.3.8 Aesthetic considerations

It's becoming increasingly important for landscapes to be aesthetically pleasing to stakeholders. It may not be good enough just to return the land to a sustainable state. People are interested in seeing varied ridgelines, avoidance of planar slopes and straight lines, diversity of vegetation, and removal of roads, powerpoles, and scrap metal and lumber.

Aesthetics is a new topic coming to mine reclamation. As described above, most mine reclamation is required for the simple purpose of increasing the aesthetics of the land. Visual aesthetics tends to dominate such talk, but a well reclaimed landscape appeals to all senses, including a general appeal of being in a pleasant area.

Mines complain that aesthetics are hard to regulate but, in several mines, it is as easy as presenting an artists rendition to people at public meeting and getting their buy-in that this would provide an acceptable looking landscape.

There is always the risk that designing a landscape that puts the goal of aesthetics above that of other goals, especially physical stability, will make a landscape with poor performance. Designers need to recognize or resist this temptation.

3.3.9 Predictability and reliability

For each of the technical areas described above, there is an immense challenge of creating landscapes that will perform predictably and reliably under a wide range of internal and external conditions and interactions. In a perfect world, final landscapes are designed to be effective for the long term. In reality, we know we cannot effectively predict or rely upon a number of factors – long-term erosion and hydrology plans, the sustainability of covers, the sustainability of maintenance or geochemical kinetics. In fact, our ability to predict future landscape performance is rather limited. Even attempting to predict the long-term performance of a dynamic and changing landscape, even on a technical level, is daunting.

Cultural items also affect predictability. Many abandoned mines have landscapes that are affected by off-highway vehicles such as trucks, snowmobiles, quads, and motorbikes. Using the reclaimed land for activities like farming, logging, and re-mining, can also have significant unforeseen impacts.

Also affecting the lack of predictability is changing regulations. Mines are constantly faced with ever-changing regulations that can ultimately mean the original standards agreed upon are no longer enough. In other words, landscape performance that is good enough today may not be good enough tomorrow.

Lack of long-term predictability in all of the sciences and engineering disciplines that impact successful reclamation has important implications for landscape engineering. This lack of predictability and reliability is the major driving force behind the certification barrier described in Section 3.2 and is leading to mines failing in their ultimate goals of limiting liability and returning the land. Greater predictability and reliability is needed but, even given major advancements, our ability to predict future performance will still be greatly limited. Mines need to avoid making guarantees and fearless predictions about long-term performance.

There are five potential solutions to this dilemma. First, mines need to avoid placing too much faith in long-term predictions. Second, they need to take a more conservative approach to creating landscapes – using the notion of a factor of safety to help ensure good landscape performance. Third, where possible, mines should attempt to mimic natural analogs. Fourth, long-term maintenance can be used to artificially limit the evolution of the site and help to increase the reliability of the site. And, fifth, if mines and regulators can agree in advance that the landscape is dynamic and will change, and that the landscape will be designed and constructed using sound engineering practices and principles, than the liability for future events can be limited by agreement..

3.3.10 Construction of landscapes

The construction of landscapes – the field work required to achieve the designs – is well handled. In most cases, it is the mine operations group that performs the major earthworks and this work is handled efficiently, especially in the reclamation of large tracts of land. The operators in particular become good at achieving the desired accuracy and take a lot of pride in their work. This group is generally quite innovative.

In some cases, some of the smaller aspects are handled by contractors, especially revegetation and sometimes small landscape repairs like fixing gullies.

At some mines, contractors handle all reclamation work and, when these contractors have the support of stakeholders and regulators, it is a powerful combination. Mines often feel that their expertise is on moving materials at mining scales and leave the reclamation side to the specialists. Finding the right balance between these two activities is a management goal under landscape engineering – how much should be built-in by large equipment and how much should be retrofit after mining?

3.3.11 Workmanship

Mines generally ensure that just about every square metre of disturbed land in a reclaimed area receives reclamation (regrading, coversoiling and revegetation). A lot of money is spent going in with small equipment to cap small bare spots or to reseed unvegetated sites. Observation has shown, however, that these small sites will self-reclaim relatively quickly and that, generally, effort should not be spent trying to fix up every spot. In some cases, large areas will self-reclaim, with wetlands often being the fastest type of self-reclamation. It is not uncommon to find that areas left to self reclaim outperform reclaimed areas, especially in terms of vegetation productivity, due to self-selection of species and those species taking maximum advantage of microtopography.

Regardless of predicted changes over time, mines should endeavour to leave behind good workmanship. Any areas bare of vegetation should be minimal, and there should not be active gullies or slumps in the landscape. While these may be acceptable at a later date, if they are occurring in the few years between final reclamation and certification, especially in the absence of extreme events, it is indicative of a sloppy workmanship and a landscape that could experience rapid change under modest events.

A familiar theme of this section is the poor handling of the smaller field details, especially those involving establishing creeks and draws. In the area of construction, creation of creeks is similarly poorly handled. Management often over-rides design criteria for rip rap or delays implementation. This kind of fieldwork is usually more of a civil project than a mining project and is often poorly handled at mining scales. The fault seems to lie more with project management than the operators who, with enough time and empowerment, seem to be able to do just about anything with any size of equipment.

3.4 Monitoring and maintenance

It has become apparent that most sites will require long-term monitoring and maintenance to continue meeting their closure goals well into the future. Mines and regulators are becoming aware of this fact and its ramifications. This section discusses typical monitoring and maintenance efforts at mines.

Monitoring can be divided into four types: compliance monitoring (required by regulators), operational monitoring (needed to support the operation such as monitoring of soil cover thicknesses during placement or pore-water pressure measurements for geotechnical stability), research monitoring (intensive monitoring of smaller areas to learn more about mechanisms and performance), and certification monitoring (required to demonstrate good ongoing landscape performance for eventual certification). See Table 3.3 for detailed examples of monitoring.

Monitoring and maintenance is generally poorly handled at most mines, likely due to a lack of recognition of the importance of these activities. Documentation of monitoring and maintenance activities is even less well handled, though important to describing and discharging liabilities for the site.

The advent of widespread use of GIS is slowly being adopted to include monitoring and maintenance activities at a few mines. Setting up and maintaining the database requires considerable effort, usually by a dedicated individual. However, this kind of documentation is critical for certification activities, determining bonding levels, and the ultimate transfer of custodianship for the land.

At least one consulting firm is using hand-held computers with specifically designed checklists to record landscape performance observations. As the information can then be automatically downloaded to a database or GIS system, this method is the future of landscape monitoring.

3.4.1 Monitoring during operation

Few mines formally monitor performance of their reclaimed areas during operation. The two types of monitoring that do occur are research monitoring of a few small vegetation test plots and informal drive-by monitoring where the reclamation specialists keep an eye on reclaimed areas during site tours.

Periodic inspections by regulators often provide the mine with a list of deficiencies to note or correct and forms a kind of monitoring.

Compliance monitoring is well done where required, but is generally done at the minimum level required by regulators. About a quarter of mines are doing water quality monitoring of streams and a similar number monitor groundwater wells for water quality.

Groundwater in particular is poorly managed at most mines. It is usually overlooked, sometimes purposefully. Some mines monitor seemingly without any real reason other than regulatory compliance. Only a few places deal well with groundwater issues. There is a general feeling that groundwater problems would be nearly impossible to remedy regardless of detection.

Landscape monitoring is poorly handled at most mines. About a quarter visited are doing some kind of stream flow monitoring and a similar number monitor groundwater wells. About a quarter monitor erosion, typically only visually. About half monitor vegetation performance to some degree, and about a quart monitor for wildlife, mostly informally. A few leading edge mines are using remote sensing as part of their monitoring program.

About a quarter of mines have research plots and a similar number of natural reference areas. About 20 percent of mines have good climate data available on site or nearby and about half have never considered the benefit or need of having or using climate data.

About 15 percent of mines are involved in setting up dormancy conditions – stopping closure and reclamation activities before they are complete. Minor maintenance continues with one or two people at or near the site taking care of it.

3.4.2 Maintenance during operation

Planned maintenance activities – such as fertilization or irrigation – are generally well handled. They are part of the reclamation cycle and are done on a yearly basis for the first few years after reclamation. If the vegetation doesn't "catch," the area will often be vegetated again the following year. Areas that fail a compliance measure (such as surface water chemistry) are usually dealt with quickly, with a focus on short-term solutions.

But repairs to the landscape are unusual. Mines are quite good at reclaiming large areas, but less apt to reclaim small areas and build in the hydrology. These areas are particularly susceptible to erosion and repair. Mines usually delay these kinds of fix-ups unless the result will bring the mine out of compliance. Mines need to become better at doing the finer work and fixing up areas that perform poorly.

One strategy employed at a couple of mines is to allow nature to identify the weak areas in the landscape, then focus on providing really strong fix-ups of these areas. For example, if a gully forms, the gully is repaired to withstand a larger event. If areas are showing poor vegetation performance, the soils are analyzed and different species more suitable to that specific location are planted. In this way, the landscape can be progressively upgraded and a greater focus can be put on areas that are performing poorly. This type of declining levels of maintenance, using a "factor of safety" in repairs, is a laudable long-term strategy.

3.4.3 Long-term monitoring

With the exception of long-term research plots and compliance monitoring, there is little long-term landscape performance monitoring conducted until closure. Not until long-term maintenance becomes a reality does formal monitoring of landscape performance start.

What is required is a long-term landscape maintenance program from the start of the exploration phase of a mine's development, and one that continues until all liability is discharged. Because the landscape is large and varied, intensive detailed monitoring of all areas is not practical.

The amount of monitoring and maintenance is often something negotiated between closed mines and regulators.

3.4.4 Long-term maintenance

Until recently, just about all mines were expected to reclaim the landscape to be self-sustaining and maintenance free – simply put, the reclaimed sites were to continue to meet the goals and exhibit good landscape performance in perpetuity, under all influences, with no human intervention. This state is likely only achievable for relatively small sites, with simple reclamation and only a few goals. The revelation that most sites will need long-term maintenance occurred in many jurisdictions in the 1990s, but some still believe anything less than a maintenance-free landscape constitutes a failure of the mine and of the regulators. It remains a contentious issue.

At 30 of the mines visited, no consideration of long-term maintenance has been given. Of the 27 that have considered maintenance, they are about equally split between planning for walk-away (maintenance-free) conditions, passive maintenance (annual reviews, fix-ups as necessary), and active maintenance (requiring people on site just about every day, for example to run a water treatment plant).

Most mines aim for a maintenance-free landscape. Table 3.4 illustrates some definitions related to maintenance-free. Most modern metal mines expect some kind of long-term maintenance. About a quarter visited are aiming for varying degrees of passive (intermittent) maintenance conditions to some extent and a quarter heading towards active (virtually daily) maintenance. Some jurisdictions refuse to consider long-term maintenance, while some insist upon bonding.

Of the 12 mines that are planning for maintenance-free conditions, only about half of these landscapes will probably continue to provide reasonable landscape performance without maintenance. Overall, about a quarter of landscapes visited will provide good performance under a maintenance free condition whereas three-quarters will require some long-term maintenance to achieve this goal. While this is clearly a subjective evaluation, some low level of ongoing passive maintenance should be considered a common outcome.

3.4.5 Is maintenance-free possible?

Maintenance-free landscapes have been promised by most mines. While some mines view this as meaning that the landscape will be free from maintenance, others believe it means they will not have to pay for maintenance. Still others believe the landscape will be maintained by the future landowner or by the government.

Table 3.5 provides an estimate of the level of maintenance may be required for various mining landforms. One can conclude that most sites will have some form of long-term maintenance. If things are done right, mines can minimize the costs of such maintenance, reduce it to a small percentage of the site area, and design and construct these landforms so they are easy to monitor and maintain.

In general, monitoring and maintenance during and after closure are two activities that mines need to better handle. Most mines are recognizing the need for ongoing monitoring and maintenance to ensure that landscapes continue to provide acceptable long-term performance. In fact, monitoring and maintenance are often a method of reducing the long-term liability.

It seems likely that most sites will have some form of long-term maintenance. Through the use of closure planning and landscape design, mines can minimize the costs of such maintenance, reduce it to a small percentage of the site area, and design and construct these landforms so they are easy to monitor and easy to maintain.

Figure 3.1 Type of closure leader

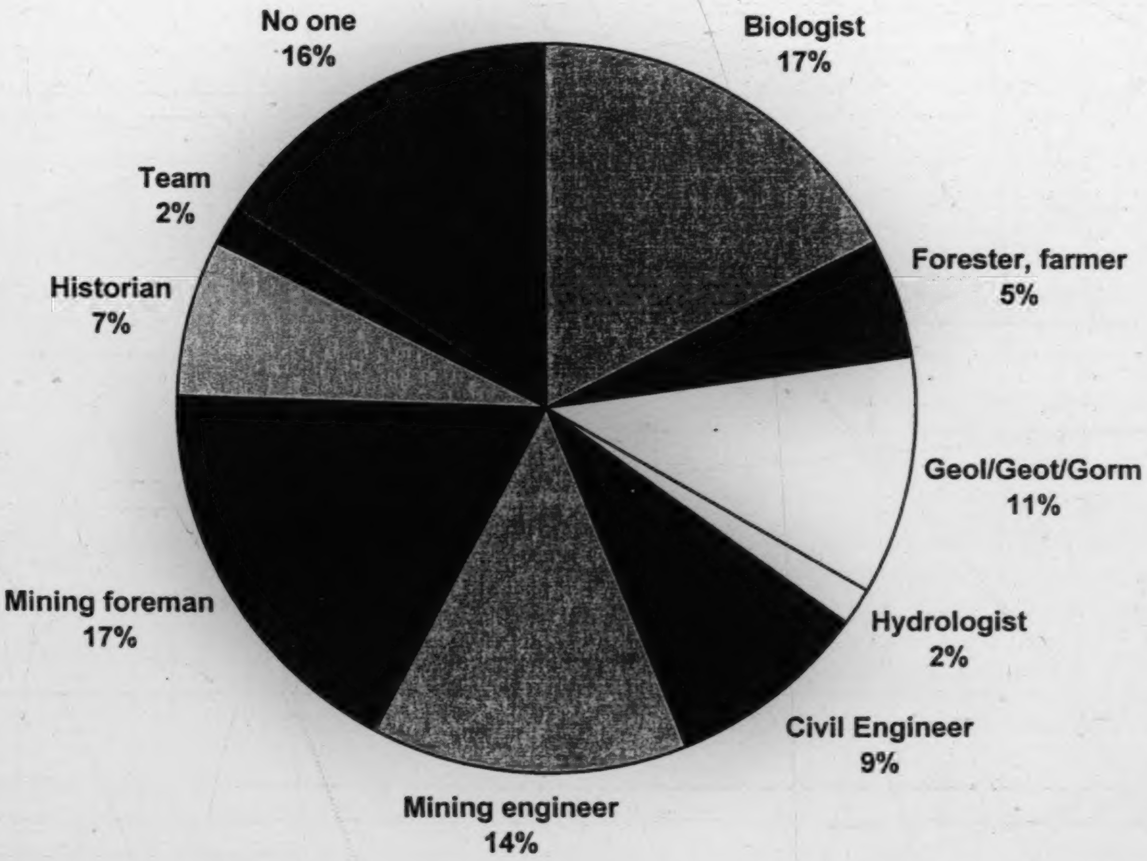

Figure 3.2 Reclamation status and closure planning status

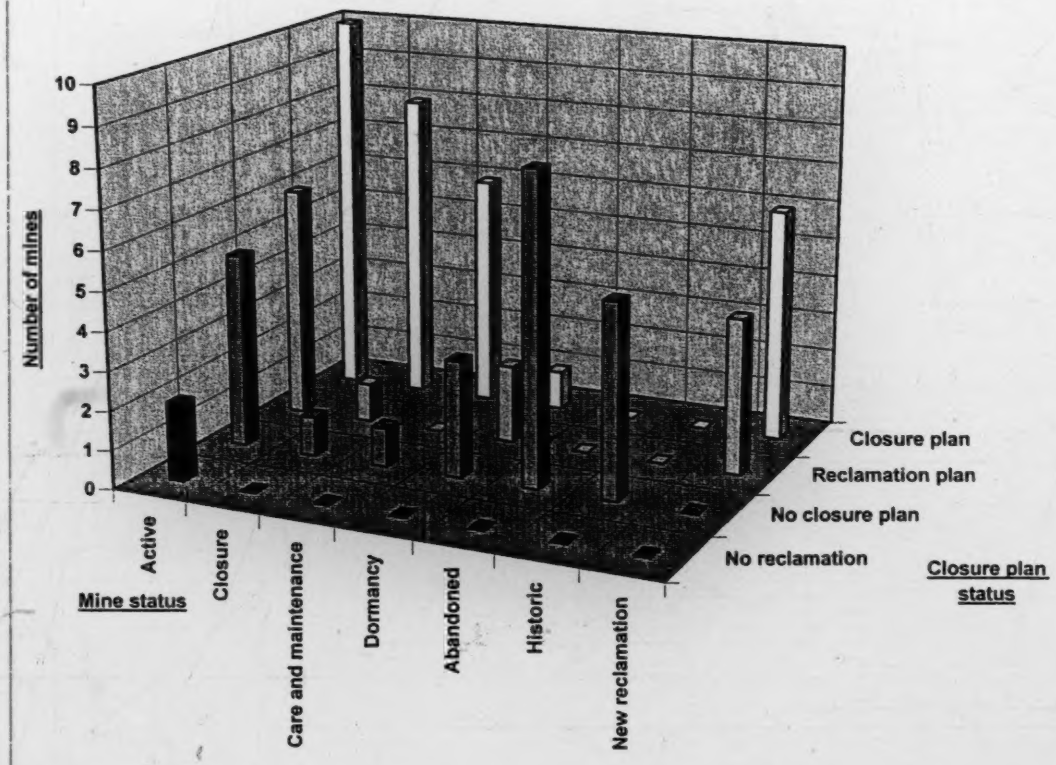

Figure 3.3 **Peak vs closure workforce**

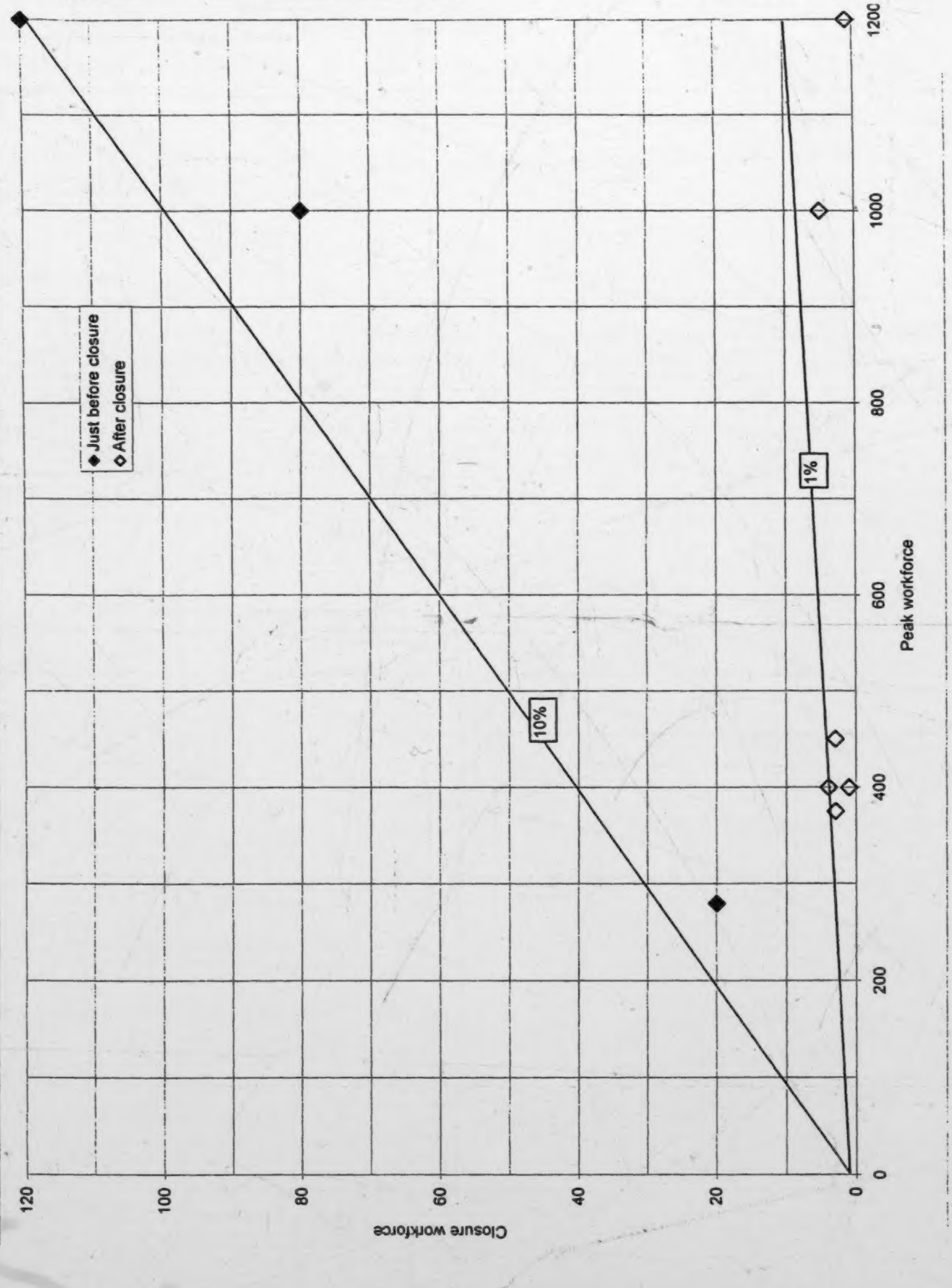

Figure 3.4 **Number one closure issue**

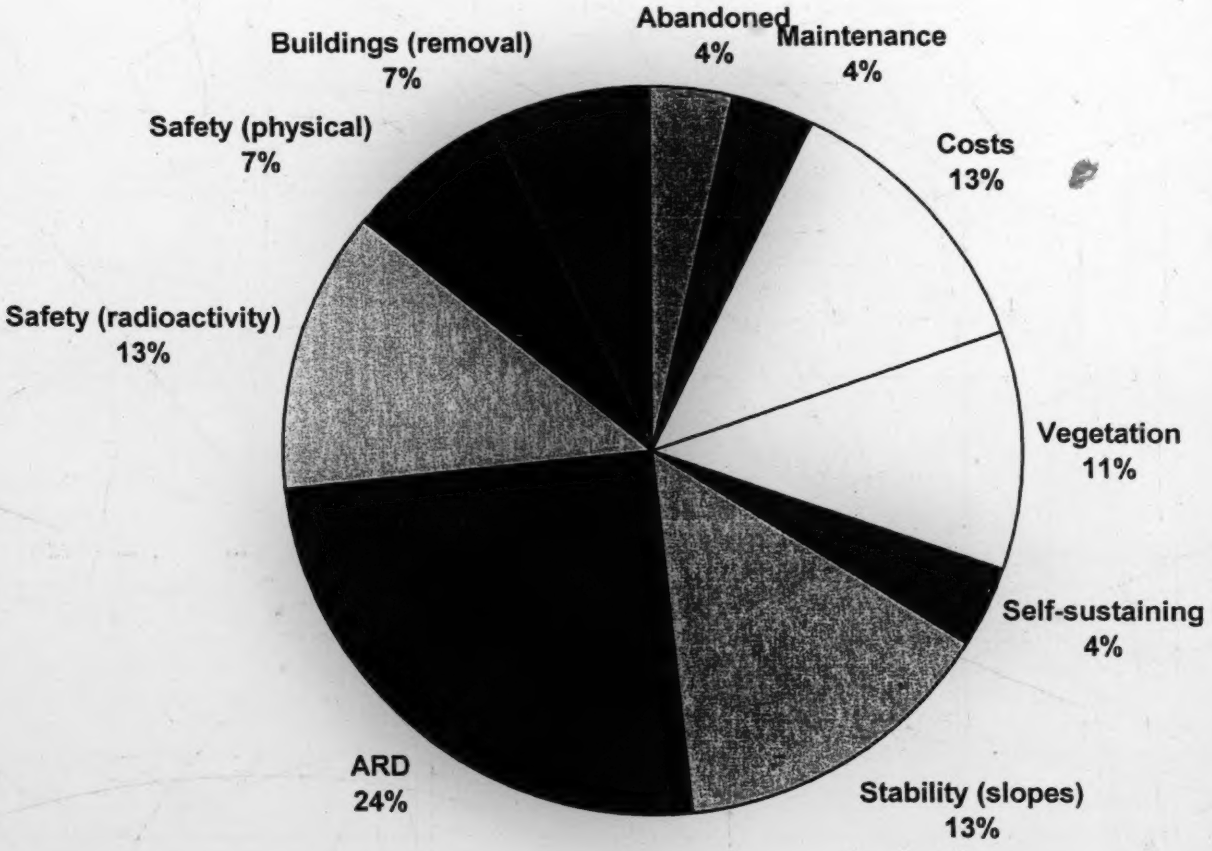

Figure 3.5 Primary and secondary goals, categories

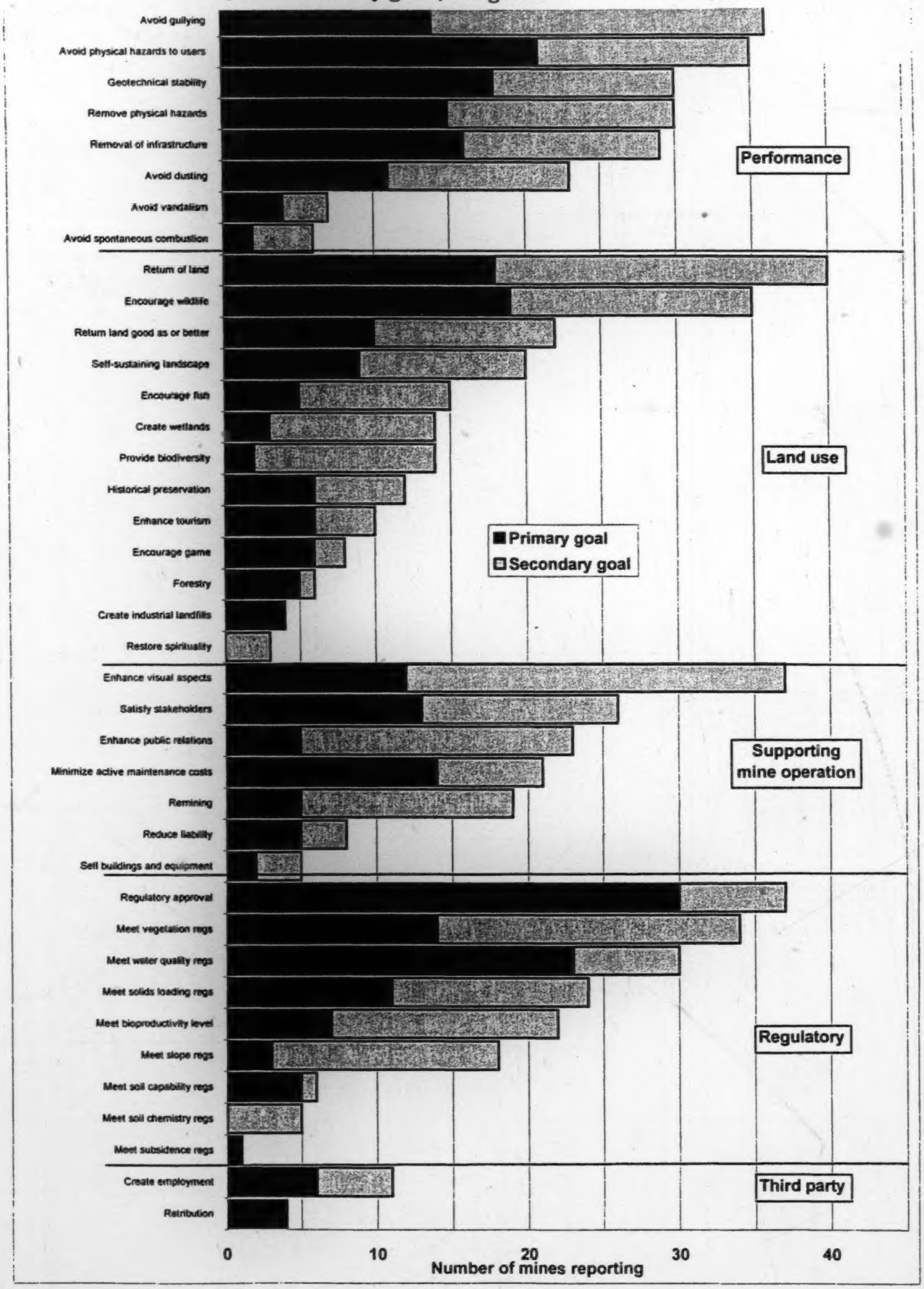

Figure 3.6 **Primary and secondary goals, all together**

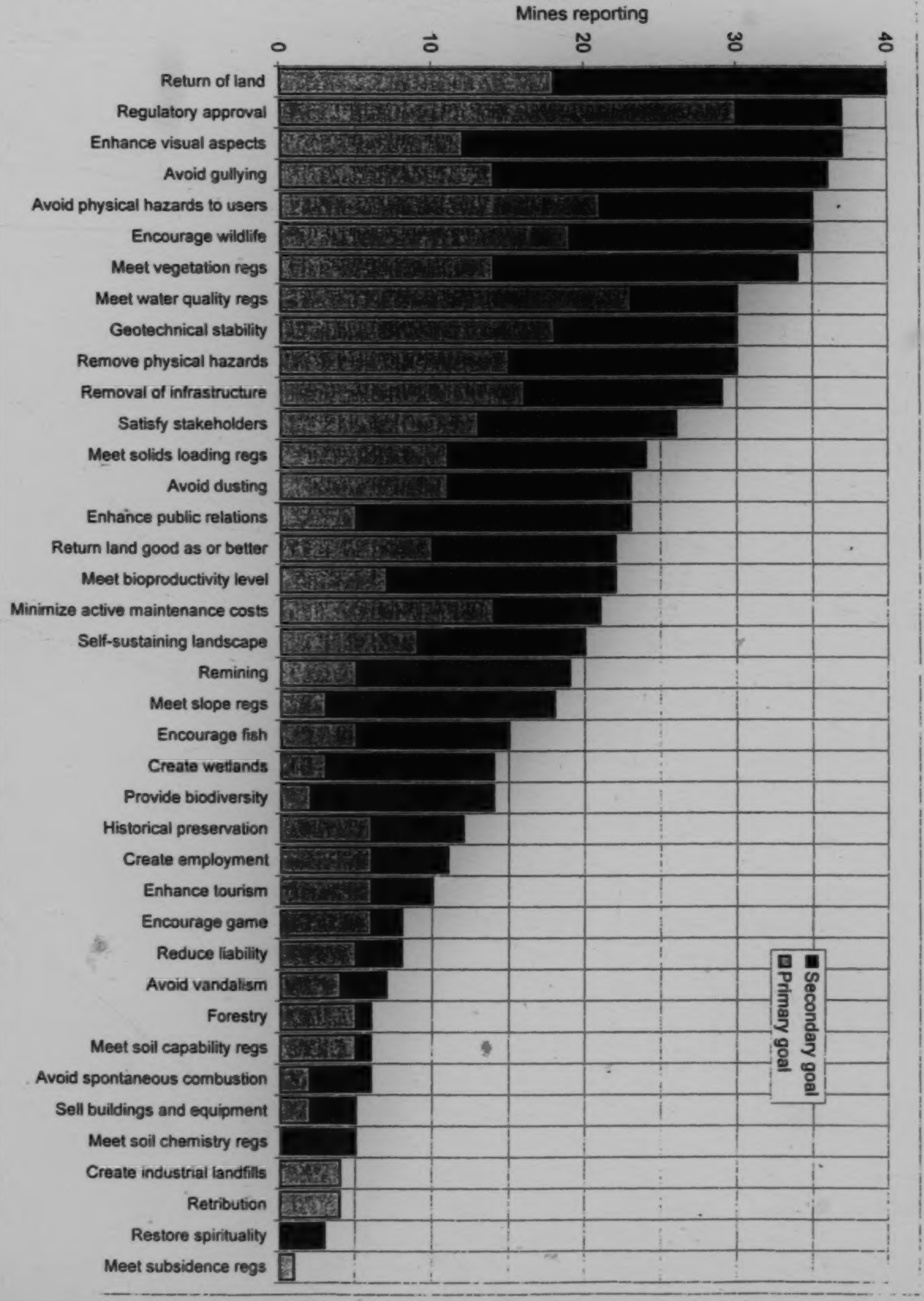

Figure 3.7 Typical design slope angles

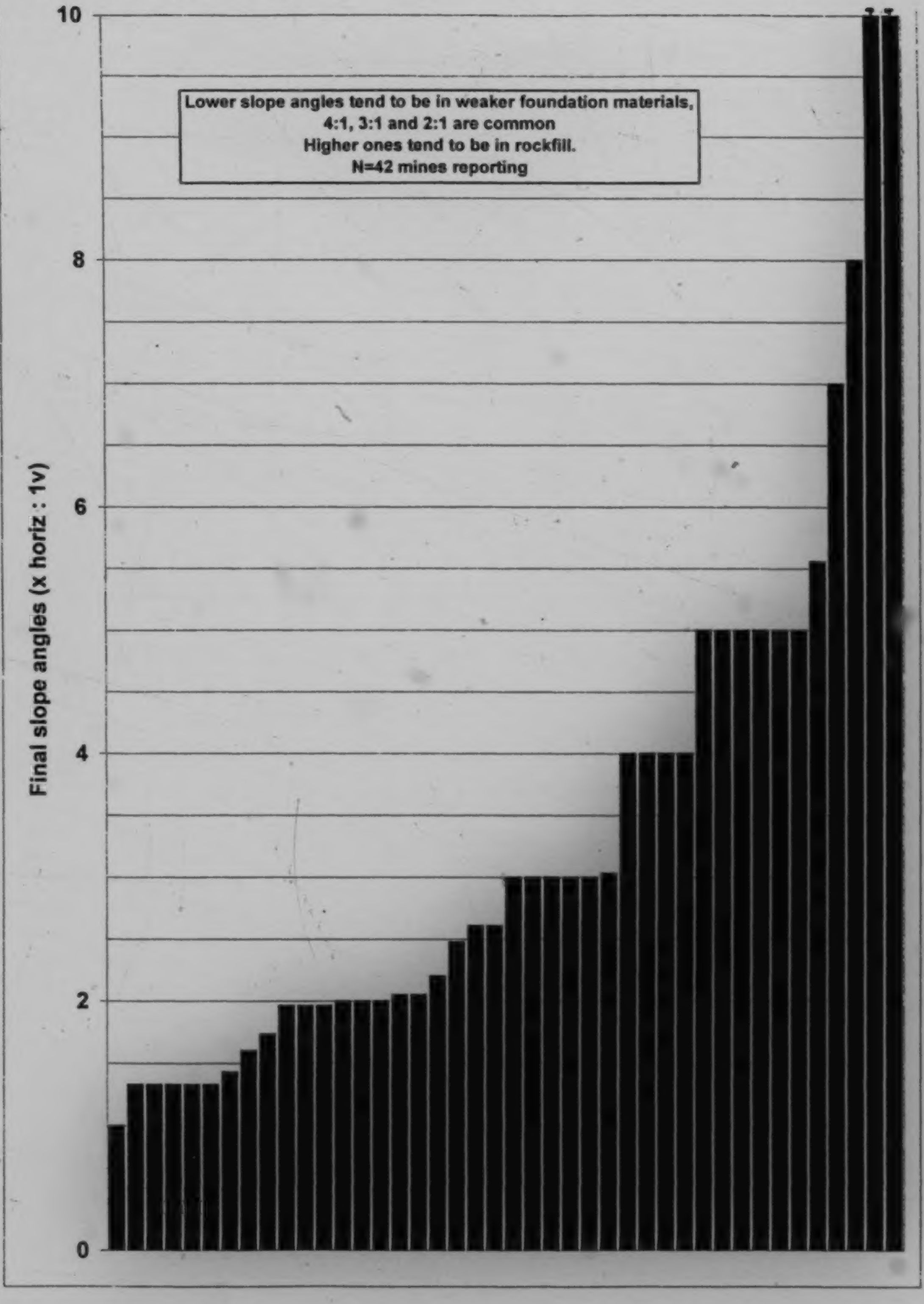

Figure 3.8 **Flood design return period**

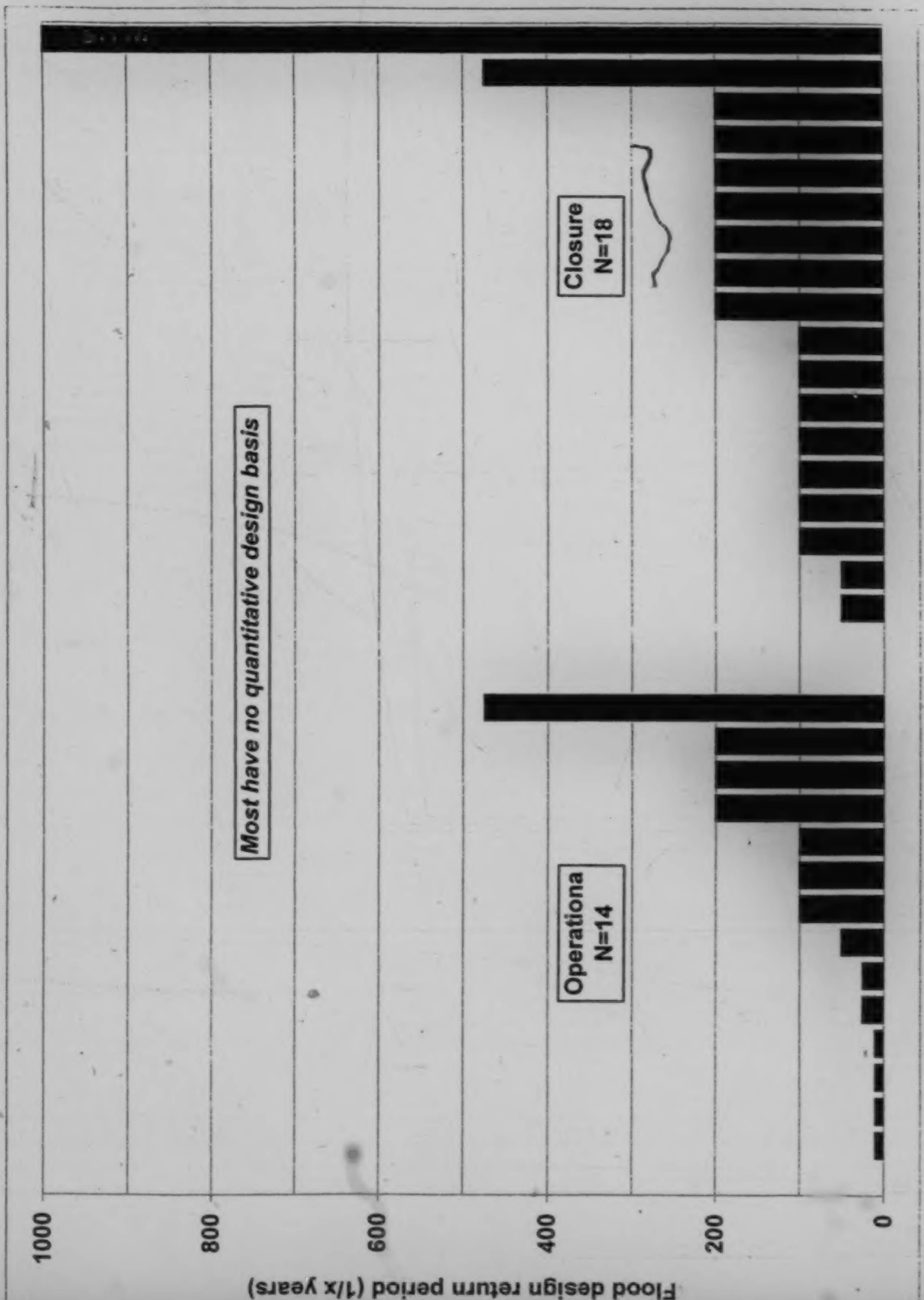

Figure 3.9 **Coversoil thickness**

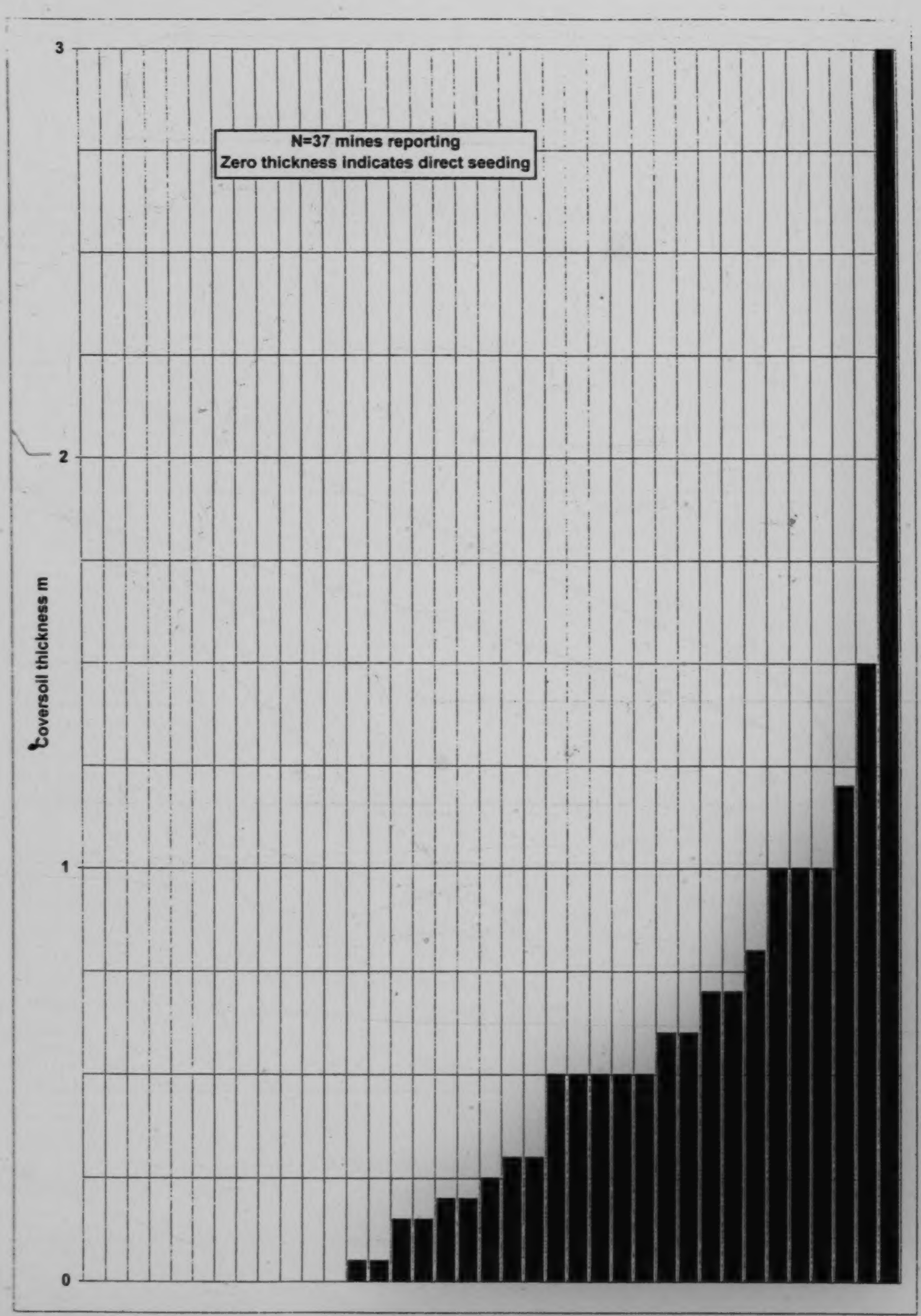

Plate 3.1 A three-dimensional model to explain the orebody and mining to stakeholders (and employees).

fording
EAGLE MOUNTAIN

Plate 3.2 A tailings pond with no reclamation plan because remining of the tailings is planned at a future date.

Plate 3.3 Wildlife is a major performance indicator of good reclamation.

Plate 3.4 **Unexpected and tricky soft tailings reclamation work costing hundreds of millions of dollars.**

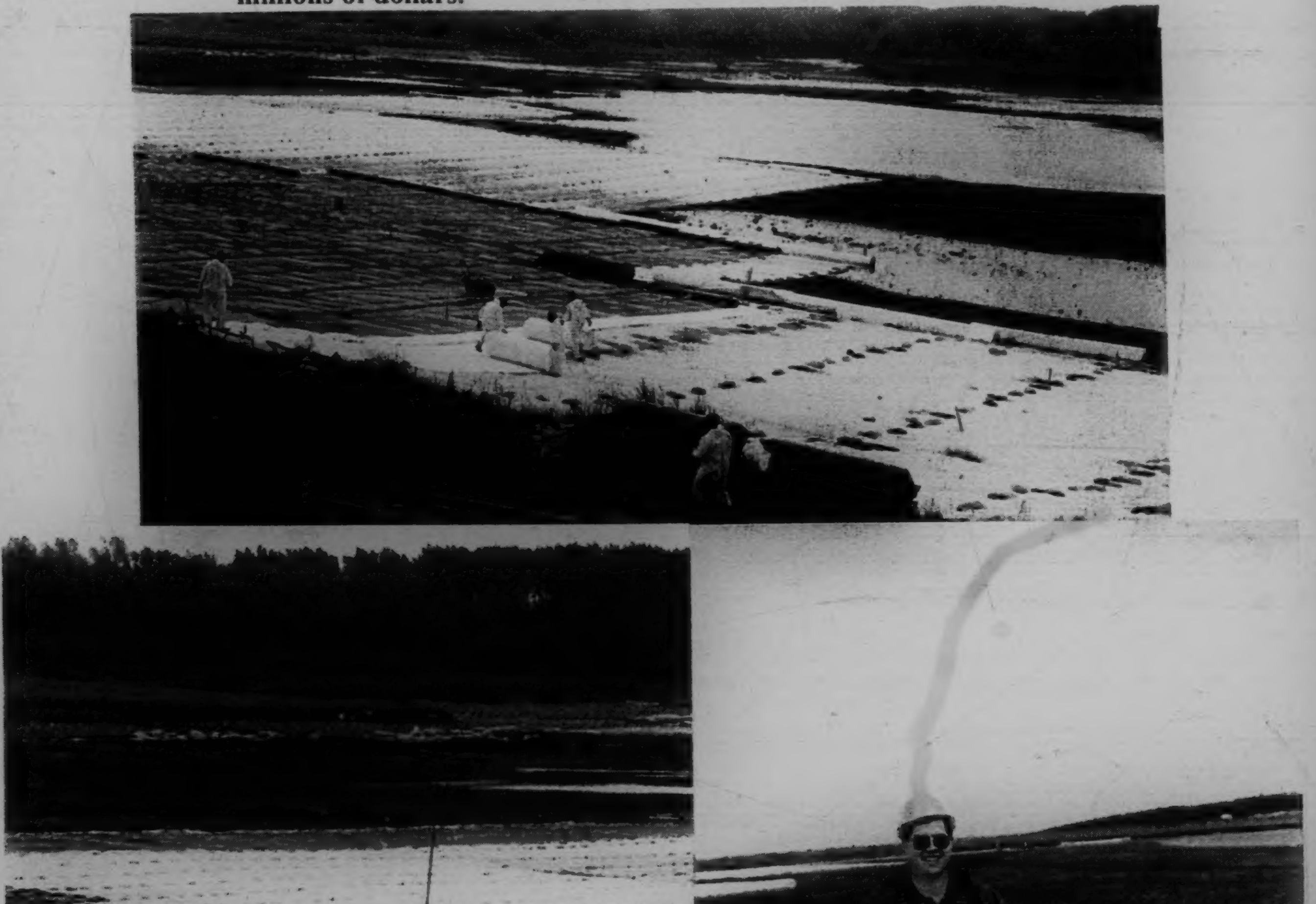

Plate 3.5 Two ephemeral creeks in the reclaimed landscape: one a broad swale designed for a 100-year flood, the other blasted into bedrock with no hydrologic design.

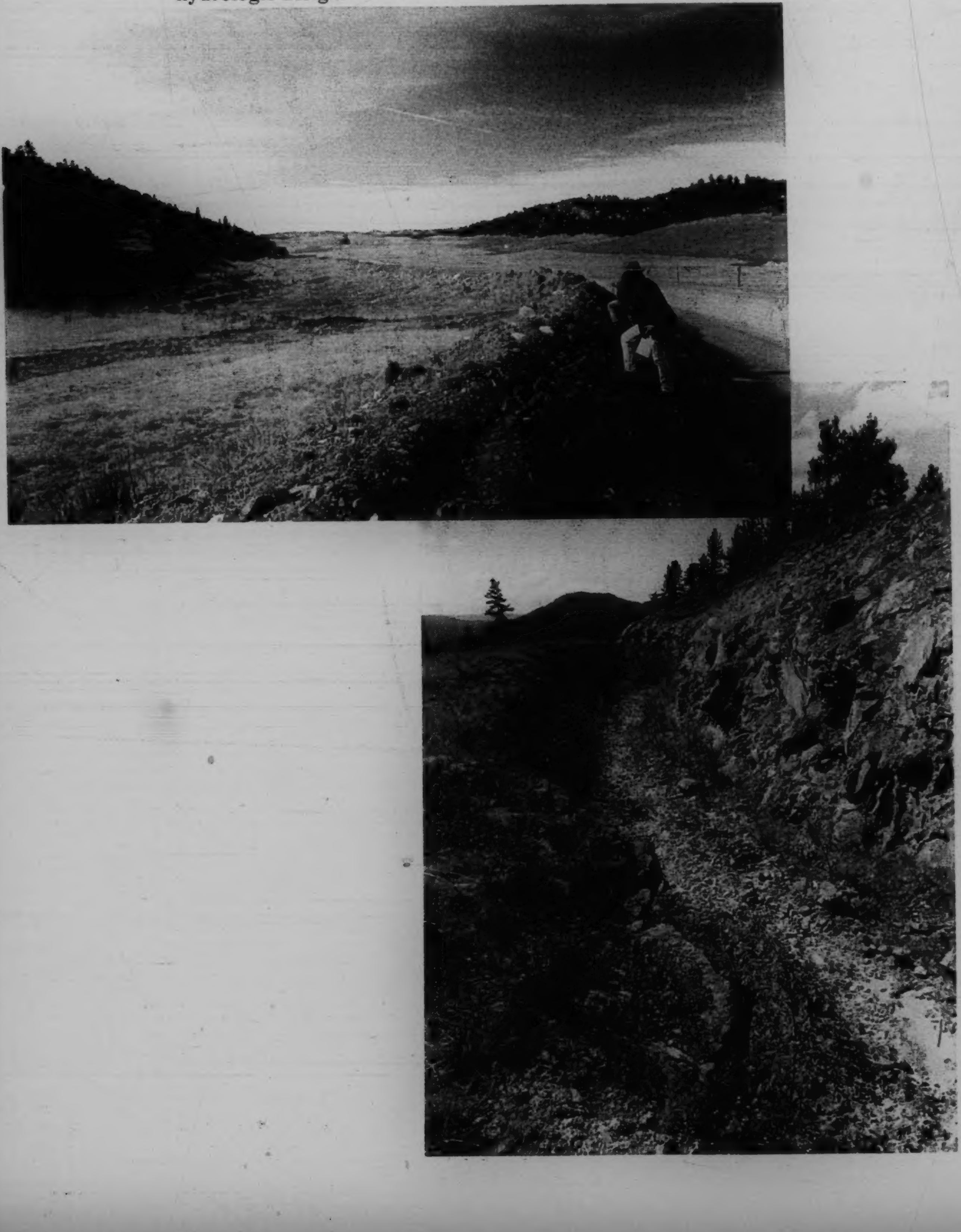

Plate 3.6 This spillway on a tailings pond was designed by a hydrologist, and the correct channel shape used, but the rip rap was too expensive and was not placed. Lower swale is undesigned and field fit by a capable dozer operator.

Plate 3.7 A ditch section at the toe of a dump acting as a permanent creek and performing as intended, but employing few of the aesthetic values. Below, a creek affected by acid rock drainage seepage water and sediment.

Plate 3.8 Groundwater issues are not always handled well. Upper photo shows unanticipated long-term seepage from the toe of a tailings dam. Lower photo shows a copper-rich ARD seep in a reclaimed area.

Plate 3.9 Permanent dust-collection monitoring site (with water treatment pond behind).

Plate 3.10 Permanent infrastructure for a closed ARD mine site that includes a 40 kilometre access road and powerline.

Plate 3.11 A modest monitoring office for pumping water to the mined out pit for eventual water treatment. Note reclaimed area and ARD seepage collection system at toe of dump slope.

Plate 3.12 Facilities for long-term maintenance often include office / workshop building and a water treatment plant (with lime storage silo).

Plate 3.13 A landslide in tills above a pit wall. Costly to stabilize.

Plate 3.14 Landsliding and other erosion along an access road.

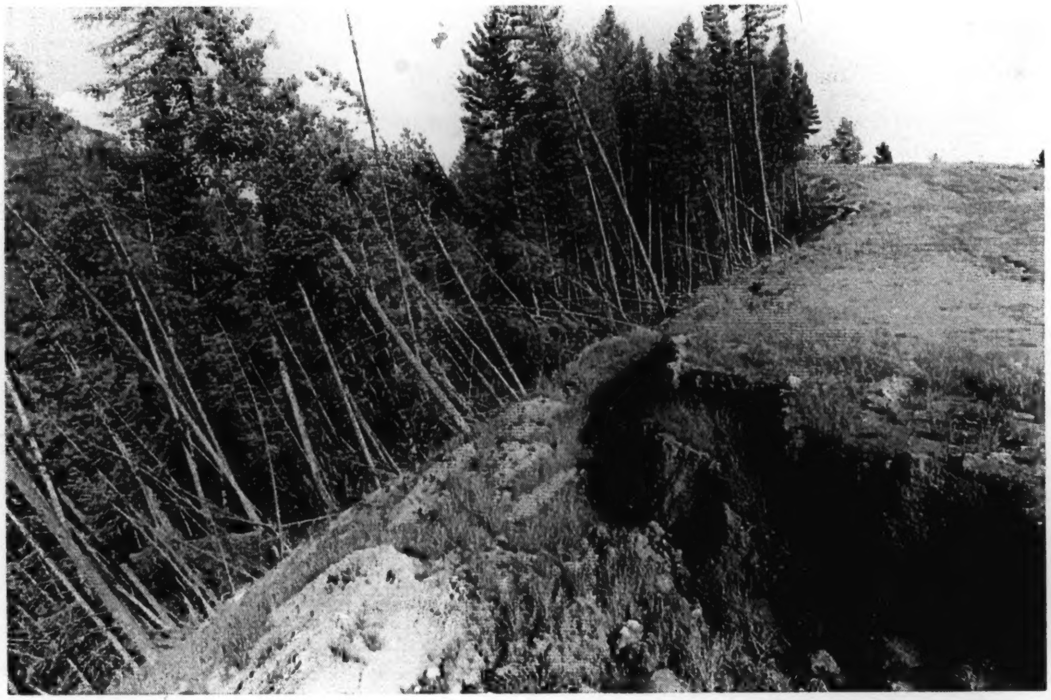

Plate 3.15 Plant site demolition at a recently closed mine. Costs could have been greatly reduced if holes in the concrete foundations had been left for blasting.

Plate 3.16 Abandoned / historic oil sand mine 35 years later. Vandalism and theft are the major concerns.

Plate 3.17 **Dormant 20-year old test pit and 50-year old mining/tailings area. Left alone, some substrates do not foster vegetation re-invasion in human time frames.**

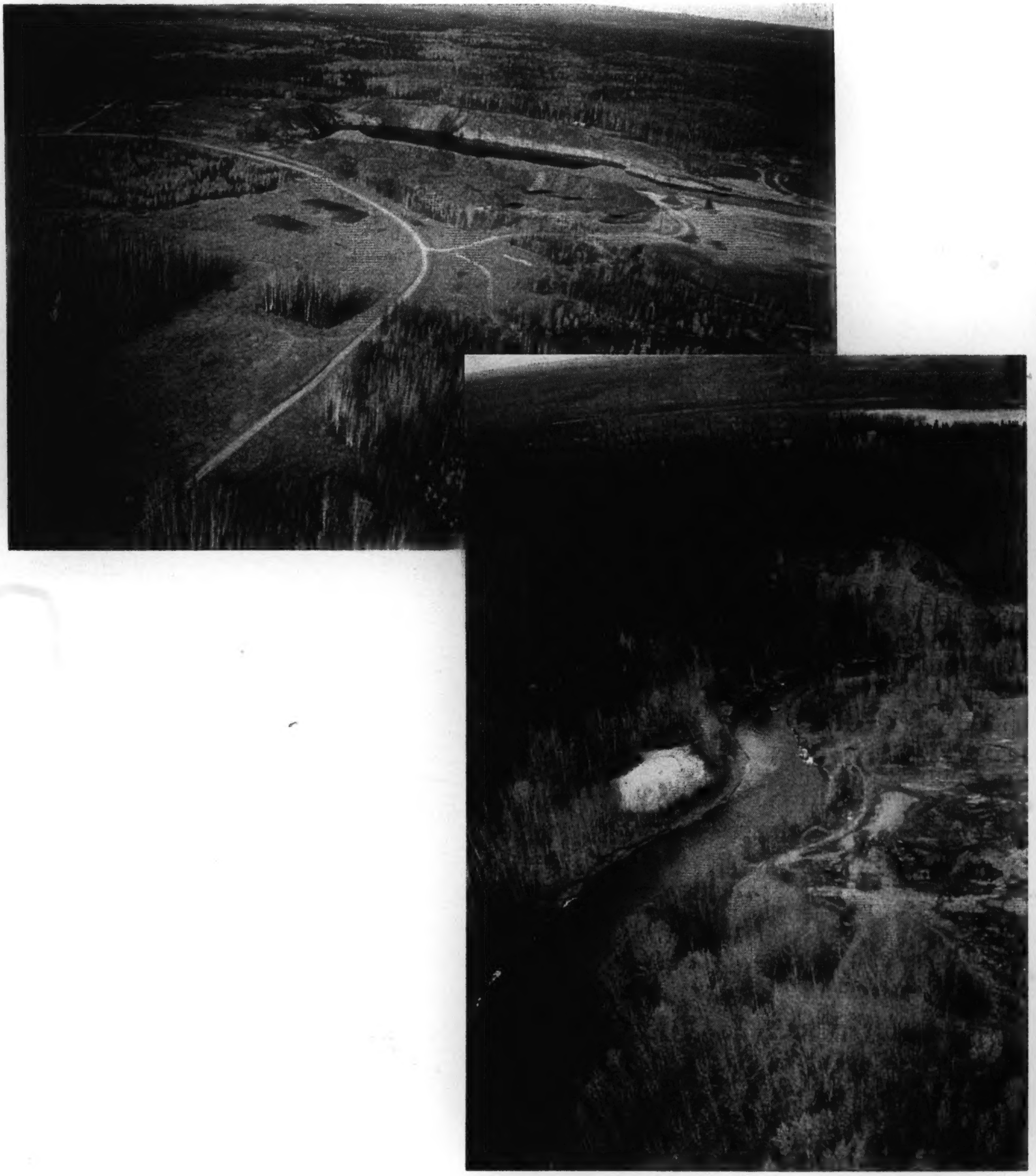

Plate 3.18 Erodible gravel slope cut a few degrees steeper than its biological angle of repose.

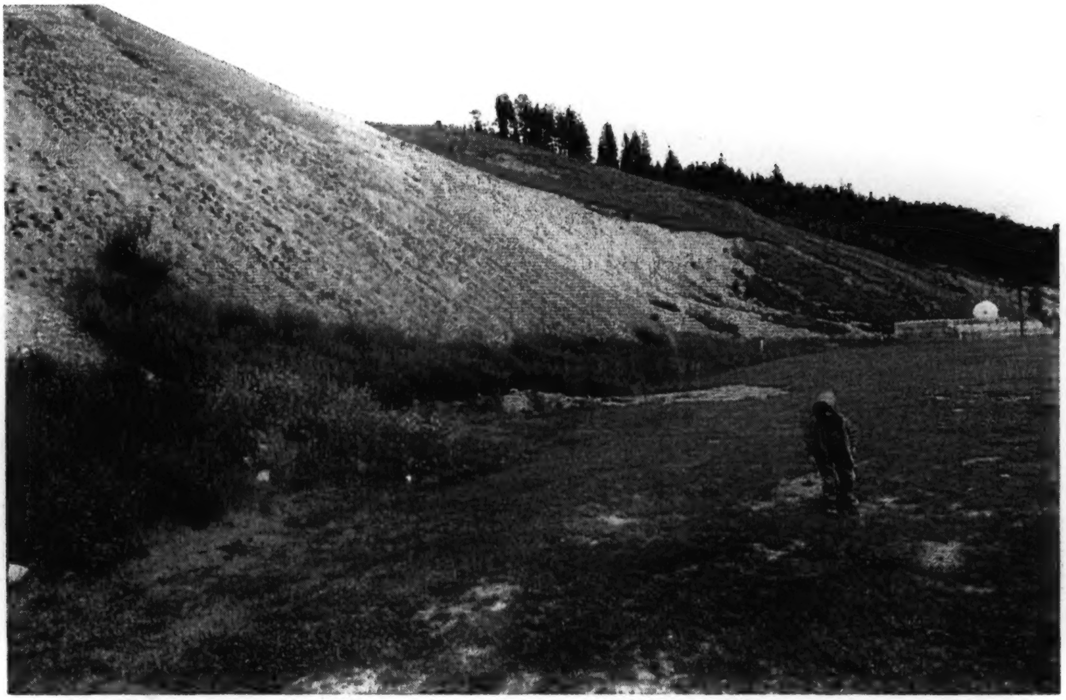

Table 3.1 List of the goals, challenges and novel concepts

A COMPENDIUM OF GOALS

Financial
- Avoid impacting other company mines by having a violation
- Bond release
- Bond roll over
- Create maintenance-free landscape
- Future re-mining
- Have same closure goals as sister mine nearby
- Keep mine open for future mining (no cover reclamation)
- Keep minesite in dormant state
- Minimize closure costs
- Minimize monitoring and maintenance timeframe
- Minimize post-closure monitoring costs and monitoring time period
- Negotiating tool
- Public relations for mining company, government, stakeholders
- Recapitalizing next economy
- Reduce liability
- Reduce long-term maintenance costs
- Return of land to original landowner
- Satisfy stakeholders
- Sell buildings and equipment
- Store water for as long as possible
- To reduce levels (flux) of ARD required for treatment
- Tourism
- Walk away (run away) unreclaimed
- Zero liability

Cultural
- Aesthetics
- Avoid disturbing archaeological sites
- Avoid hard erosion control measures
- Avoid sabotage
- Avoid vandalism
- Build good will among stakeholders and regulators
- Don't restrict livestock wildlife with fences
- Employment/jobs/construction company/spending others money
- Historical preservation
- Involve the community in research and reclamation
- Limit vehicular and other unauthorised access (trespassing)
- Remove scrap and trash
- Retribution
- Road reclamation
- Satisfy local residents
- Visual similarity

Regulatory
- Avoid declination or certificate
- Avoid non-natural materials
- Cover mine waste
- Don't be too complicated
- Meet soil capability guidelines
- Meet vegetation requirements, especially percent cover
- Meet water quality (on site and off site)
- No subsidence
- Pork-barrelling
- Regulatory approval/compliance
- Solids loading and offsite erosion /deposition criteria
- To remove any contaminants from the site
- Uniform slopes with no gullies, potholes or depressions
- While in its dormant site, have it meet environmental regulations

Physical
- Avoid aeolian erosion
- Avoid animal erosion
- Avoid off-site seepage contamination
- Avoid river erosion
- Avoid seismic damage
- Avoid spontaneous combustion of (coal) spoils
- Cleanup and removal of infrastructure
- Cover bad materials
- Geotechnical stability
- Have little erosion and no off-site erosion.
- Low risk to human health
- Maintain water cap
- Removal of physical hazards
- Restore aquifers
- Use micro- and meso-topography to control erosion and add diversity

Land-use
- Chose land uses that are the cheapest to create
- Commercial forestry
- Create a hydroelectric facility
- Create a mix of land uses
- Create aquaculture
- Create farmland
- Create fish habitat
- Create gardens or spas
- Create grasslands
- Create industrial park
- Create landfills
- Create natural area
- Create park
- Create ranchland
- Create wildlife habitat
- Recreation
- Return land to original land use
- Return of original land use
- Traditional land use

Biological
- Creation of wetlands
- Edge effects for wildlife
- Equivalent land capability
- Good as or better than mining or better than before revegetation
- Green up historic mining areas
- Green up the site
- Kick-start the natural successional process
- Meet a bioproductivity level
- Meet soil chemistry requirements
- Mimic reference area
- Not to favour coyotes
- Planting diversity
- Promote rare wildlife (bats) or exotic wildlife
- Provide diversity of slopes and veg
- Restore damaged offsite lakes
- Restore native vegetation (non-exotic)
- Rocks for rodents
- Soil conservation
- Sustainability
- Water for cows

Chemical
- Store water
- Water discharge without treatment

Other
- Able to drive a truck over it
- Create test areas
- Just be stable
- Manage water infiltration and runoff
- Meet personal needs
- Meet professional requirements
- Mimic natural conditions
- Return spirituality to land
- Stop human habitation
- To create long-term employment

A COMPENDIUM OF CHALLENGES

Design and planning

- Abandoned mines
- Closure planning separate from daily operation
- Competing goals/objectives
- Complete lack of design
- Complexity
- Do what you do well, ignore the rest
- Eternal optimism vs geologic and ecological reality
- Existing structures
- Future owner abuses site
- Imperfect understanding of nature
- Keeping track of commitments
- Lack of a system:
- Lack of data
- Lack of precedence
- Lack of reliability, predictability
- Lack of staff, outside influence
- Loss of records, staff turnover
- Low factor of safety
- Low grade stockpiles
- Missing key hazard
- Site never had a closure plan
- Stakeholder involvement
- Surface water hydrology ignored
- Too focussed on biology
- Too focussed on physical stability
- Too focussed on meeting regulatory requirements for bond release
- Trying to satisfy all people all time
- Unclear objective
- Unknown unknowns, unknown hazards, chemical x
- Unreasonable or poorly understood designs
- Very little research or monitoring

Reclamation operation and construction

- Cannot get commitment back at home to do what has been agreed to
- Contract specifications and field flexibility
- Reclaiming next to active tailings beaches
- Reclamation affected by ongoing operations
- Redisturbance by operation
- Widespread use of waste material

Monitoring and maintenance

- Active maintenance of large areas
- Active maintenance with a finite lifespan is planned
- Allowing whole site to become maintenance intensive
- Aquatic vegetation and pumps
- Costly site access
- Data management
- Defects take years to appear
- Hard to go back and fix something that's already reclaimed.
- Irreparable damage caused before monitoring would detect problem
- Lack of electrical power
- Lack of maintenance
- Lack of monitoring
- Long term active maintenance
- Maintenance without access
- Mitigating effects of offshore tailings and waste rock
- Research takes too long
- Risk of losing access or power for water treatment
- Risk to research sites
- Too much study, not enough doing
- Water treatment sludge volumes

Financial

- Closure bonding is often in the tens to hundreds of millions of dollars
- Government is starting to apply fixed financial criteria to closure bonding.
- Historic mining
- Inherited liability when purchased
- Instantaneous closure
- Low or fluctuating commodity prices
- Net-present-value (or cost) economics
- Owner or government doesn't want it
- Sedimentation ponds may require active maintenance
- Unreal expectations of walk-away
- Unreasonable commitments

Cultural

- Disturbances by ATVs
- Fencing and grazing concerns for vegetation
- Goals of regulators, stakeholders, and miners in conflict
- Identifying leaders in stakeholder groups
- Minesite close to habitation
- Minesite experiences trespassing and vandalism
- Mine town closure
- Opponents to mining
- Smelter continues to operate indefinitely
- Staffing problems at closure
- Stakeholder apathy
- Wildlife grazing on vegetation

Regulatory

- Bizarre regulations
- Changing regulatory requirements
- Cleaning up to background levels
- Coal surcharge paying for AML
- Dealing with dormancy from a regulatory point of view
- Government owned lands, intergovernmental conflict
- How to fix things when unfixable
- Imported regulations
- Ineffective regulators
- Intervention of politicians and powerhouses
- Long time lags to certification
- Not challenging regs of beliefs
- Power of individual mines
- Power of individual regulators
- Too complex for regulators
- Unclear, conflicting, overlapping, and numerous regulatory goals
- Unreasonable time frames
- Variable regulations between states and countries
- Visual overriding physical realities

Physical

- Autocompaction
- Changing infiltration rates
- End pit lake performance
- Establishing drainage on flat areas
- Extreme climate
- Geotechnical instability leading to further poor performance
- In maintenance, no provision for extreme events, no risk assessment
- Leaving behind tailings dam & pond
- Long term geotechnical stability
- Mountain top end-pit lakes
- Physical risks to people and animals
- Rock fall hazards
- Seismic risk
- Site hydrology poorly understood
- Site underlain by pervious substrate
- Subsidence

Chemical

- Acid rock drainage
- Close proximity of mine wastes to environmentally sensitive area
- Disposing sludge water treatment
- Groundwater ignored
- Large amounts of ARD producing material
- Long term leaching
- Mitigation of deep-lake or ocean disposal
- Problem soils
- Radioactivity

Land use

- Some agreed upon land uses difficult to achieve

Biological

- A major game-fish stream flows through the site
- Animal effects on erosion
- Animal effects on vegetation
- Beavers
- Climatic variability
- Hard to re-establish vegetation
- Lack of organic soil
- Redisturbance
- Use of native species

Other

- Education in remote areas
- Hazardous conditions to workers

COMPENDIUM OF NOVEL CONCEPTS

Design and planning

- Adaptive science
- Aim for no ongoing liability
- Annual environmental audit
- Avoiding problem habitats
- BADCT Best available demonstrated control technology
- Burying of worst waste at depth
- Closure planning to establish research priorities
- Decision analysis
- Diversity
- Early monitoring
- Ecological engineering
- Establish a corporate commitment
- Focus on minimizing liability
- Honest effort is what counts
- Landscape architecture
- Naming conventions
- Planning horizon limited to 50 years
- Recognition of exploration damage
- Recognition that every site is unique
- Risk assessment
- Risk-based criteria
- Self-design reclamation
- Team approach
- Trial and error reclamation
- Use of design principles

Reclamation construction

- Acid mine drainage control through planning
- Active maintenance of checkdams
- External review and audit
- Field fitting reclamation and terraces
- Going offsite for capping materials
- Paste backfill
- Removal of entire waste dumps and tailings ponds
- Removal of entire waste dumps and tailings ponds for placement in mined-out pit
- Removing trash
- Rounding of pit crests
- Specialized reclamation equipment
- Stockpiling reclamation soils on haul roads for eventual closure of the roads
- Use of a well-known, well-respected contractor consultant for all biological reclamation work

Monitoring and maintenance

- Annual reports
- Good use of signage
- Long-term monitoring plans
- Modem communications and alarms to permit offsite monitoring and control of pumps
- Photo spots and tour spots
- Slump and gully fix-ups are being done as required
- Standardization of equipment
- Use of GIS
- Use of remote sensing
- Yearly site monitoring and maintenance.

Financial

- Blurred division between mining and reclamation
- Buying liability with minesite
- Estimating closure costs
- Historical legacies
- Land value not equal to reclamation cost
- Liability needs to be continually updated for shareholders.
- Liability of commodity purchaser
- Logging of the site to support reclamation costs.
- Purchasing the outstanding shares
- Recognition of benefits of progressive reclamation
- Steady budgets
- Time of the essence
- Transparency in reclamation and decision making

Cultural

- Beautify highly visible areas
- Build and donate an interpretive nature centre in a reclaimed area
- Clean up messy areas
- Creation of golf courses
- Donation of area for clubhouse
- Fishing derby
- Formation of local stakeholder groups
- Getting local service groups or stakeholders to do reclamation
- Grazing problems
- Historical tailings
- Involving the president in reclamation
- Native employment
- Natural looking reclamation
- Religious blessing of land
- Stakeholders may not like reclamation construction activities
- Uranium tailings in plaster
- Use full-scale demonstrations
- Use of boardwalks
- Vandalism
- Visual barriers
- Yearly planting by members of the community

Regulatory

- Difficulty in dealing with naturally occurring ARD
- Hard to assess sustainability when monitoring temporary measures
- Move problem onto reservation or active site
- Overall government agency
- Poor decisions by regulators
- Pound of flesh

Physical

- Allowing gullies to form, then repair/armour them to become permanent features
- Avoiding plateaus
- Cat tracking downslope to build in rills
- Complete hydrologic design manual
- Diversity in soil, vegetation and, slopes
- Drainage down old haul ramps
- Infiltration into these coarse dumps limits erosion
- Loss of aquifer
- Microtopography with a backhoe, rocks, roughness
- Segregating surface waters
- Shotcreting of waste-rock dumps to limit infiltration
- Steep-walled channels for self-armouring by eroding banks
- Watershed as an end land use

Biological

- Avoiding fish
- Bats and special wildlife, fed elk
- Biosol (human sewage) to act as a fertilizer/organic amendment
- Direct seeding of coal wastes
- Dumps at repose can be revegetated.
- Introduced species
- Irregular limits for wildlife
- Planing mature trees upside-down to provide perching habitat for eagles
- Preservation of damaged areas
- Reference areas
- Rock piles for wildlife
- Shotgun seeding
- Species diversity for long-term cover
- Sustainability as an end land use
- Underground tree nursery
- Use of shrub islands for diversity and to aid in natural invasion

Land use

- Aquaculture in old thickener and end pit lakes
- Garbage dumps in mined out pits
- Jail as an end land use
- Solar neutrino observatory

Table 3.2 Examples of unrealistic or high-risk goals

Type of unrealistic or high risk goal	Examples from the 69 mines visited
Promises that go against nature	• planting exotic trees in the desert • creating self-sustaining oasis in desert • no erosion on planar slopes • wildlife can be kept from feeding on metaliferous vegetation
Promises with no definition	• create rich biodiversity in final landscape where biodiversity is not defined • make the land better than it was before
Promises based on development of future technology	• agreeing to plant rare species that have never been planted • agreeing to develop or breed species are tolerant to elevated salts or metals • agreeing to use only native species for all areas of landscape • agreeing to develop new computer models for prediction • agreeing to develop new (or less costly) water treatment system • agreeing to develop new tailings disposal methods
Promises with low probability of success	• a promise to create a maintenance-free landscape in tough ARD conditions where everything would have to go perfectly for success • use of passive wetlands for bioremediation of metals • avoid release from water treatment areas during extreme precipitation events
Promises that are technically impossible	• the site will have no erosion • no subsidence of a compressible fill will occur • restoration of original contours everywhere • meeting dozens of promises simultaneously • no erosion of fills placed on floodplain
Promises based on complex numerical models	• complex computer models that show certain end-pit lake performance far into the future under all conditions • ecological succession models to show future growth and ecosystem development • achieving certain habitat suitability indices for wildlife
Promises with-open ended timeframes and promises that cannot be tested in human time-scales	• perfect performance in perpetuity • zero probability of any geotechnical instability • promises of good performance in the probable maximum precipitation event (PMP) or probably maximum flood (PMF) • no unwanted groundwater contamination for 10,000 years • perfect performance of internal filters and pipes in tailings dam
Promises that are not self-sustaining or ignore natural ecological succession	• using grassy patches for wildlife in a dense forest • creation of specific ecosystems at odds with soils or aspects
Promises with that ignore economic reality	• backfilling of all mined-out pits after closure • use assets at closure to pay for reclamation and bonding • maintain levels of employment present during mining • zero liability at a complex site • estimation of liability with precision • clean up of all wastes to background levels
Promises that ignore human nature	• have no damage from trespassers on fragile sites • keeping fish from lakes and streams
Promises that are conflicting	• commercial forest and traditional land use • recreation and wildlife • natural species and intensive agriculture • full remediation and historic preservation • perfect ongoing performance and maintenance free • original contours (with new materials) and erosion free • aesthetics versus landform stability • logging on tailings sand slopes

Table 3.3 Types of landscape monitoring

Monitoring type	Reason	Example	State of practice
Compliance	Regulatory requirement	• Groundwater wells • Surface water chemistry • Annual report	Well handled; sometimes limited in extent; often data only reported, not analyzed.
Operational	To guide day to day operations	• Soil cover thicknesses during placement • Slope inclinometers/ piezometers for slope stability	Common; well handled; documentation and data management sometimes lacking.
Research	To learn more about performance and adjust future activities	• Vegetation plots	Most have few small areas that receive intensive monitoring for many years
Certification	To demonstrate good record of landscape performance and trends	• Annual photographic records • Maintenance records • Periodic tree growth assessment	Generally infrequent; data not generally managed
Informal	Allows specialists to evaluate whether treatments are effective and maintenance is required	• Drive by assessments of vegetation lushness, volunteer species, erosion	Occurs at all mines; no documentation; guides annual activities
Third party	Periodic inspection, usually by regulators	• Field tour • Annual review of documents	Generally restricted to regulators; sometimes as a liability audit upon purchase

Table 3.4 Maintenance-free definitions

Definition	Result
The landscape will be free from any maintenance	Even if the landscape would benefit from maintenance, none will be done.
The landscape will be free from maintenance by the mining company – the government will maintain the landscape in the same way it maintains elements of the natural landscape	The mine assumes no liability for any long-term maintenance. Most commonly assumed by mines.
The landscape will continue to provide acceptable long-term performance without human intervention	No maintenance will be required to have acceptable landscape performance in perpetuity regardless of extreme events or internal changes. Most commonly assumed by regulators.
The landscape will have no elements commonly associated with long-term maintenance	Assumed to have no dams, reservoirs, ongoing water treatment.
No scheduled maintenance, just fix-ups after major events	Suggesting that active maintenance would not be involved, but passive maintenance on an occasional basis would count as maintenance free.
Some new level of landscape performance will be acceptable without maintenance.	The landscape is designed to be maintenance-free (designed to meet all goals in perpetuity), but people would be willing to live with lesser performance without maintenance.

Table 3.5 Typical levels of long-term maintenance for various mining landforms

Landform	Maintenance level (for reasonable assurance of continuing good long-term performance)		
	Walk-away	Passive maintenance	Active maintenance
Tailings dam / reservoir			✓
Tailings slopes		✓	
Tailings level areas	✓		
Dumps – at repose	✓	✓	
Dumps - resloped	✓		
Dumps – level	✓		
Dumps – engineered / capped		✓	
Chemical contaminants			✓
Pitwalls	✓	✓	
End-of-pit lakes	✓	✓	
Rivers	✓	✓	
Sedimentation ponds and checkdams		✓	✓
Shafts and portals	✓		
Fences and infrastructure		✓	✓

Table 3.6 Examples of landform grading

Mine	Landform grading activity
Syncrude Mildred Lake	• Landform grading trial on a 85 hectare site, with integrated drainage, microwatersheds (one to three hectares) and contoured plateau
Castleridge 1-4	• Mounds created with small backhoe to create microtopography (one metre scale).
Bell	• Three-metre high mounds (dumped by haul trucks) on the top of a dump to create better wildlife habitat
Island Copper	• Sculpted shorelines / embayments at 100-metre scale where dumped waste rock creates a rocky beach along the ocean.
Highvale Coal	• Landform grading along sight and sound berm, 50-metre scale – microwatersheds with tailored planting
Line Creek Coal	• Five-metre high mounds at the 20-metre scale on dump to provide wildlife habitat • Landform grading of dumps to blend better with mountainous topography
Suncor Tar Island	• 300-metre scale ridges along river valley

Note: Many of these examples do not embody all aspects of landform grading, but can be considered early examples of this technology.

4.0 FINDINGS: LANDSCAPE PERFORMANCE

4.1 Terrain unit performance

Terrain analysis has long-been used to categorize natural landforms. This idea has been extended to elements of artificial landforms by Professor Dave Cruden of the University of Alberta. Using this breakdown, generic landscape performance of various terrain units can be described. This section provides a qualitative evaluation of the major terrain units found at many minesites.

4.1.1 Tailings plateaus

Slightly less than half the sites visited have tailings dams (most coal mines do not have tailings dams and many uranium mines have remote dams at regional mills).

The sandy beaches seem to be generally easy to reclaim, and are sometimes direct seeded or capped with a thin layer of reclamation material. Aside from the occasional area (say five metres in diameter) of poor vegetation performance, they are generally performing well. Beaches that have a water table near the surface (due to poor underdrainage) can have trafficability problems but, once reclaimed, seem to perform well.

The soft tailings areas at the distal ends of beaches are extremely expensive to reclaim. Based on results from the 1999 Soft Tailings workshop, typical costs are about $200,000 per hectare (10 to 20 times normal reclamation costs) to stabilize and reclaim these extremely soft deposits. After reclamation, subsidence and ponding continues to be a long-term problem with no ready solutions. Water treatment costs for the process-affected waters at closure can also be immense and unexpected.

Sometimes the ponds are turned into freshwater lakes, with considerable success. Usually a spillway cut into bedrock is required. Establishing trophy sport fishing in such ponds goes a long way to enhance stakeholder acceptance of these ponds.

Dusting from tailings areas during active operations is a concern for most mines but can usually be brought under control through vegetative, soil, or water cover soon after closure and is not usually a long-term closure issue.

So other than two major exceptions (flushing of contaminants out the toes or into the foundation materials) and trafficability problems on soft tailings, tailings dams and reservoirs are performing well and relatively easy to reclaim.

Some mines, especially oil sands mines, are finding that the water balance is such that the beaches will have perpetually high water tables making trafficability difficult. For these sites, hummocks are planned to provide areas with lower water tables (separated by broader wet swales).

Implications: Sandy beaches are usually easy to reclaim and perform well. Soft tailings areas are extremely expensive to reclaim and often provide little value once reclaimed. Methods to minimize the area of soft tailings at the surface of reclaimed tailings ponds is needed.

4.1.2 Tailings slopes

Where the downstream slopes of tailings dams are made of tailings, performance is generally poor. Almost all downstream tailings slopes are composed of silty sand or sand, which generally has both poor infiltration and water holding capacity.

The result is that it is often difficult to create a continuous healthy vegetative cover on tailings sand slopes- rilling and gullying is common. Some areas experience minor slumping (especially in areas which have slightly finer tailings), and some exhibit evidence of solifluction-like creep behavior. Areas that need irrigation to establish the cover are susceptible to gully erosion due to sprinkler pipe leaks and breaks. Where seepage exits at the toe, vegetation is usually sparse and spring sapping can sometimes be observed. Slopes constructed of cycloned tailings sand fare slightly better.

Where the dam has a large rock starter dam, long-term seepage control seems to be assured. But where filters and off-takes are used to control drainage, many mines expect long-term maintenance to keep the internal plumbing system active.

There is also a concern about the effects of animal grazing or erosion by all-terrain vehicles on some of these tailings slopes. The vegetation cover is often fragile. Once a gully is able to cut through the vegetation or soil cover, erosion occurs rapidly and the gullies are not usually self-healing.

The result is that many, if not most, tailings sand slopes are performing poorly and have doubtful long-term performance in the absence of periodic maintenance. Alternatives to having tailings on the downstream slope may be useful to consider, given the cost and intensity of maintenance of these slopes.

Furthermore, most are a constant source of leaching of metals or acid rock drainage. Many were built with a substantial waste-rock starter dam without recognition of the metal or acid producing nature of this rock and thus have created a virtually permanent source of contaminants that will require long-term water treatment.

Implications: Tailings sand slopes are nearly unreclaimable – that is, they are unlikely to meet stability and land use goals. If employed, many will likely require ongoing periodic monitoring and maintenance. Additional efforts into the design of such slopes is needed. Recognition is needed that most tailings dams are the source of groundwater seepage of metals or acid rock drainage which will usually require long-term maintenance.

4.1.3 Dump slopes at their angle of repose

Dumps (overburden storage areas) are sometimes left at their angle of repose in the final landscape. Typical angles are about 35 degrees. These slopes are generally of coarse rock, which accept virtually all precipitation as infiltration.

Aside from the fact that it is rare to see substantial vegetation on these slopes, they are performing well. Erosion is minimal and they present minimal risk. They may offer some benefits to some kinds of wildlife.

Some repose slopes are vegetated, particularly ones that have a finer component and a bit of cohesion. However, these slopes are susceptible to shallow slip failures and solifluction-like movements, probably related to local variability in the permeability and concentrations of groundwater flow and the associated loss of cohesion.

Often the materials in dumps contain ions that leach out over time, particular acid rock drainage (ARD) producing materials but also materials rich in molybdenum or salts. Long-term leaching of these materials is generally inevitable and may lead to poor landscape performance. Elaborate covers are often designed to limit infiltration, but most of these require active maintenance to either remove volunteer trees, repair subsidence cracks, or other general maintenance.

Long-term seismic stability of dumps at repose may be an issue.

In general, leaving dumps at repose is generally frowned upon or outright prohibited, usually due to the lack of vegetation. In some cases, it may make sense to leave these dumps at their angle of repose, depending upon the stated goals for landscape performance.

Implications: It seems likely more dumps could be left at their angle of repose without affecting the overall site performance. But where this occurs, efforts need to be made to ensure the dumps do not offer a long-term geotechnical stability hazard.

4.1.4 Resloped dump slopes

The slopes of most dumps are resloped to angles of 2H:1V or flatter. Terraces are usually included in the slopes, but the reasons for the terraces are often not understood. In fact, their use is usually prescribed.

Most resloped dumps are performing well. A few gullies will form over time (particularly in finer grained dumps) but these do not generally impact greatly on overall landscape performance. Slumps at the toe happen occasionally, particularly if the dump is oversteepened by having a toe ditch too close.

Vegetation on these slopes is usually easy to establish, except in desert areas.

The design of the terraces remains a problem. Thought to be the final word in slope design, their role in limiting erosion by sheet flow is often marginal as water usually flows over the berms. The berms will help to limit downslope migration of small gullies but, in ponding water and resultant overtopping of the berms, they often lead to increased erosion.

There is an interesting ongoing debate whether to tip berms in, out, or given them a constant elevation. The answer would seem to be to either tip them out (and design for longer slope lengths) or to tip them dramatically inwards and laterally so that the water flows to armoured downswales.

The intersection of two dumps deserves special attention in erosion protection as the water concentrating at the intersection usually gullies.

The berms also give an artificial look to the landscape, though their geometric regularity is usually hidden if a dense tree-cover is used.

Quite a few mines are experimenting with forms of roughening dumpslopes, creating small mounds and hollows to increase topographic, soil moisture, and vegetative diversity. These seem to be acting well, despite not being formally designed. If the watersheds are small enough, medium scale ridges and swales area being effectively used at several mines as a form of landform grading that has both good erosion performance and topographic diversity.

Microtopography is a tool that is being more widely used. Instead of leaving planar surfaces, 10 to 20 centimetre holes and mounds and 10 to 20 centimetre high downslope ridges are being incorporated into slopes. This creates microrelief and changes in microaspect for the slopes that enhances moisture retention and plant growth. This work is in its early stages and is presently being demonstrated rather than researched. Suitably employed, erosion may also be reduced while enhancing wildlife habitat.

A common problem for slopes is water ponding on the top plateau, which causes explosive gullying as it reaches the crest. The shallow ponds then flow suddenly down the slope, causing large gullies and the start of a new surface water drainage system for the top. No slopes can resist the gullying of overtopping.

Many dump slopes are performing fairly well, especially if they have small watersheds. Larger slopes are showing signs of gullying, due to ponding or concentration of water.
Long-term performance of these slopes, aside from the erosion concerns for some, is expected to be fairly good.

Implications: Resloped dumps generally show good performance, but a better system of designing and controlling overland flow is needed.

4.1.5 Dump plateaus

Dump plateaus are usually performing well. Generally, they are capped and vegetated, and the vegetation performs well. Erosion on the plateaus is small.

In some cases, differential subsidence leads to the formation of shallow ponds and wetlands (or just puddles) on the tops of these dumps, particularly finer grained ones. This can result in wet soil conditions and sometimes to overtopping events where the ponds overtop the crest of the dump and cause the slopes to gully.

Implications: Dump plateaus are generally performing fairly well but need to be designed to minimize negative impacts of subsidence and the potential for shallow ponds overtopping the crest and causing slope erosion.

4.1.6 Dumps – engineered / capped

Engineered covers are complicated to design and construct and mines are presently having difficulty in providing reliability in design, construction and performance. Many mines avoid placing engineered covers on waste rock dumps due to concerns about cracking from settlement.

Dumps with engineered covers to limit deep percolation are generally performing fairly well, though the ability to reach the desired percent infiltration goal is often spotty. Many mines are able to achieve percolation rates of 10 to 15 percent, but many are hoping for much lower.

Vegetation generally performs well on these engineered covers, but sometimes too well – volunteer trees are often removed periodically to maintain cover integrity from tree roots. Good long-term performance of most covers is probably contingent of periodic maintenance.

Engineered covers (especially for ARD) are fairly complicated for a variety of reasons:
- highly technical
- unproven long-term performance
- expensive
- require lots of research
- require that trees be kept from surface (active maintenance)
- consider enhanced leaching to reduce contaminating timeframes
- many mines focus on short-term chemical costs.

Implications: The science of designing engineered caps for dumps to act as percolation barriers is rapidly increasing, but the performance of the caps is difficult to predict. Many will require long-term periodic maintenance to ensure they remain effective.

4.1.7 Chemical contaminants

Most mines have mineralized waste rock and those with tailings ponds have mineralized tailings. Control of these chemical contaminants is being well handled through active measures. Aside from spill conditions, contaminants are usually kept on site and treated if necessary. Rates of contaminant loading are difficult to predict and easier to measure.

Implications: Mines need to be more aware of chemical hazards, particularly with the tailings and waste rock. Better monitoring programs are required and closure regulations. Declarations about plumes and potential for treatment need to be clear.

4.1.8 Pitwalls

Highwalls are generally left unreclaimed, largely because they are difficult to reclaim and most jurisdictions do not require their reclamation. Some mines are experimenting with hydroseeding of coal-pit highwalls, an example of corporate requirements exceeding regulatory ones.

All pitwalls show evidence of active spalling and about a quarter of those have semi-active landslides.

Little can be done to remediate hardrock pitwalls. Sometimes the land use is successfully adjusted to call this area escape terrain for wildlife or nesting areas for birds. Little can be done economically. In some soft-rock mines, the pitwalls are pushed down or hydroseeded with minor success.

Buttressing of highwalls is required at many U.S. mines although, while the buttresses usually perform well, this is an expensive endeavour.

At oil sands mines, it is typically the plan to backfill or reslope highwalls.

Most hardrock mines fill with water to become lakes and the pitwalls continue to spall, sometimes presenting hazards to people. Most mine slopes have large semi-active geotechnical slope failures which sometimes are made more stable due to pit filling and other times made less stable.

Many mines are minimizing the hazards of people and wildlife inadvertently falling down the pitwalls by installing extensive fences or berms, along with signage. Some are rounding the pitwalls.

Most jurisdictions recognize that pitwalls will remain a geologically active historical remnant of mining.

Implications: It is generally accepted that pitwalls will continue to spall and fail unless buttressed. It is unreasonable to expect most mines, especially hard rock mines, to fill, reslope, or buttress their slopes, so residual hazards and risks remain. In some cases, fencing or other measures may be desirable to minimize hazards to people or wildlife of falling off these cliffs.

4.1.9 End-pit lakes

End-pit lakes are common, in fact, almost every mine will have one. Interestingly, most mines planning for an end-pit lake view it as a unique and surprising challenge. Mines and regulators need to start working together to gather data and support research work on end-pit lakes if they are to be built economically and reliably.

The filling rate and final elevation of end-pit lakes is often predicted and the predictions relied upon, but the evidence reveals that there is low reliability of these predictions. Most pits fill four to six times faster than expected due to a poor understanding of the site water balance. Unless there is an excess of water flowing through the pit, which is unusual, it is very difficult to predict the final elevation of the end-pit lake – some end up much lower than predicted, others much higher.

The poor prediction of end-pit lake filling rates and elevations means that water treatment plans often have to be moved forward by 10 or 20 years and the treatment plants built quickly.

Many end-pit lakes will contain tailings in the bottom while others will contain water treatment sludges, which tend to also have a very large volume.

The limnology of end-pit lakes is also difficult to predict. Thermoclines, haloclines and chemoclines abound. The water balance is difficult. Most lakes have small areas of littoral zones, and so generally have clear water and low productivity.

Implications: More effort needs to be spent understanding the site wide water balance and the performance of lakes, and a more conservative approach needs to be made in predicting pit filling rates. For now, it is safe to say that pit filling rates and final water levels are unpredictable.

4.1.10 Rivers and creeks

Most mines visited have no formal design for rivers or creeks. Of the few that have been constructed, only a couple received formal design and most are simply field fit. That being said, present performance of almost all the few rivers and streams seems good. Bank erosion and solids loading to streams seems minimal. Suitability as fish habitat seems minimal.

But few of these watercourses are likely to maintain their good performance during even modest floods. Most have highly erodible substrates and will require extensive repairs after such events.

The lack of design and the likely poor performance of rivers, creeks, and areas of overland flow are major deficiencies in the present reclamation and closure work.

Implications: These streams need to be designed, construction needs to follow design, and periodic monitoring and maintenance, particularly after extreme events, is likely required for ongoing good performance.

4.1.11 Shafts and portals

Designs for sealing of shafts and portals has received a lot of attention in the literature and is generally well done. Methods usually include gates or large concrete plugs.

One problem for this technology is the ingenuity of trespassers. Many mines, especially in the U.S., have had people remove or bypass these portals, leaving them open for others to fall into. These trespassers use acetylene torches to cut through gates or explosives, drill and blast methods to bypass the plugs, presumably to explore the old mines, or seek treasure in terms of old mining equipment or remaining gold, minerals, or fancy crystals.

Implications: Not much more can be done to seal shafts. Periodic inspection and repair of damaged plugs may be needed.

4.1.12 Fences and infrastructure

Fences and infrastructure generally perform well, but require periodic maintenance.

Implications: Where used, these facilities will have to be monitoring and maintained.

4.1.13 Wetlands

The use of wetlands in mine reclamation is a popular topic but few were seen in the mine visits, perhaps since many mines are not in regions usually associated with wetlands.

The few wetlands observed seemed to be performing well. Most are classified as marshes – they are predominantly open water and are fringed with emergent and semi-emergent aquatic vegetation. Most form opportunistically. The key is the hydrology of the wetlands which is often extremely difficult to predict in advance.

Some mines are interested in the potential of wetlands as bioremediators of everything from sediment to naphthenic acids, salts and metals. The long-term performance of such systems is unclear and probably should not be relied upon as an effective measure for critical performance goals unless monitoring and maintenance is planned.

Implications: Wetlands seem to form well naturally and benefit from elements of self designed. Marsh-type wetlands could be more widely incorporated into reclaimed areas as they have a large number of benefits and seem to be easy to create. In that the hydrology is difficult to predict, mines need to be careful about promising too much performance from their wetlands.

4.2 Whole-landscape performance

The performance of each mine landscape as a whole based on a brief site visit is difficult to ascertain. One also has to postulate criteria for overall performance. If one were to postulate that whole-landscape performance could be acceptable if:

- off-site effects were acceptably low
- the site seems capable of meeting some low level of landscape use (as in being green)
- that risks of future catastrophic events were small
- maintenance levels were generally low.

Based on these simple criteria, about 80 percent of the sites seem capable of meeting this standard. The ones that don't are generally ones that have major components of their functioning overlooked, such as groundwater plumes, lack of major surface water drainage systems, or inability to establish a reasonable vegetative cover over large areas.

That overall landscape performance based on simple overall criteria seems generally obtainable, while meeting specific goals and having good performance for every landform with high aspirations for land use will be extremely challenging for most mines, suggests:

- with modest efforts, landscapes can be reclaimed to at least "do no harm"
- having good performance everywhere in the landscape is difficult. It comes down to a question of scale – at what scale is good landscape performance required?
- incremental increases in performance are both expensive and require higher levels of design effort and higher levels of monitoring and maintenance.

This discussion highlights one of the major findings about landscape performance, one that is seldom considered explicitly. Landscape performance depends on the scale of the inspection[13]. We've seen that at the landscape (or regional) scale, which encompasses the whole disturbance and possibly the surrounding areas, that the reclaimed landscapes can generally be made to perform well. At the landform scale (say 100+ hectares), most areas will perform well while some areas will require more effort and attention. At the micro scale (say one square metre), some areas will not pass (for example, they will be actively eroding, they will have elevated levels of some undesirable chemicals or ions, they may be unvegetated). So any question of assessing landscape performance must deal explicitly with scale.

Failure to specify performance based on scale makes mines liable to the whim of regulator. It essentially confirms the notion of unlimited liability. Clearly, a regulator would not fail a landscape based on poor performance of a single square metre of landscape, but how many and what size of poorly performing area would constitute failure? We must resist the effort to try to come up with prescriptive criteria for such excursions but, at the same time, decide upon acceptable scales. But based on intuitive reasoning, one might suggest that any more than about 10 to 20 percent of a given terrain unit that fails to live up to its agreed upon goals is probably enough to fail this unit.

It also suggests that small disturbances of about a couple of hectares are much less likely to show poor landscape performance than large ones – not only on a complexity and technical level, but just on the scale that the regulations are enforced[14].

4.3 Meeting goals reliably

As described above, mines usually have dozens or hundreds of regulations to adhere to as well as numerous goals for the landscape. Goals are usually not defined well enough to allow a clear decision on whether they have been achieved and efforts to define them, including measurement techniques and endpoints, are not likely to provide additional value.

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[13] This follows a parallel of geomorphic indeterminacy which shows that the prediction of behaviour at very small scales is not possible, but at larger (e.g. landscape), more accurate predictions are possible (for example, see Leopold, 1963)

[14] It would be counterproductive to try to prescribe the scale upon which reclamation is regulated. Instead it involves site specific aspects and common sense interpretation – and perhaps most importantly, trust between the mine and the regulator.

But using common sense it is often clear when the general goals of reclamation are met (at least for short-term performance). But in most cases, there is significant doubt whether they will continue to be met in the long-term, particularly in the absence of long-term maintenance.

In fact, there is little assurance that mines will generally meet their reclamation and closure goals, and even less that long-term performance will be acceptable. This is caused by overselling the intended performance on the reclaimed landscape and by general uncertainty in trajectory and behaviour of the landscape under unknown and perpetual forces. Mother Nature always bats last.

It is this uncertainty in meeting long-term goals, and the liability associated with this uncertainty that has caused the certification barrier – mines and regulators are unwilling to sign off on meeting the long term goals.

Mines have the habit of promising too much from the reclaimed landscapes and need to remember not to promise what can't be delivered. In particular, professionals need to counsel their companies and clients on making what may end up being extravagant claims about the landscape including such items as promising an early return to pre-disturbance productivity levels, maintenance free status and zero erosion.

In fact, not much can be promised – there are simply too many failure mechanisms and interactions between mechanisms to be able to provide reasonable assurance that the landscape will meet any but the most basic of goals. A mechanism of setting modest goals and designing landscapes to meet these goals reliably is clearly required. Perhaps more importantly to mining companies and regulators, a mechanism for transferring liability of well constructed sites is needed.

Reliability and predictability are a big concern for landscape performance. This is especially important in light of the fact that long-term liability for future performance is still unresolved.

4.4 Decommissioning, certification and custodial transfer

Decommissioning refers to the final activities to prepare the land for certification and custodial transfer. It is usually involves removal of improvements (buildings, pipelines, etc.), and finalizing the reclamation (fixing slumps, bare spots, armouring gullies, building rivers, etc.). Certification goes by many names but refers to the final inspection and approval of reclaimed and decommissioned land by government regulators. Custodial transfer is the formal transfer of the land to a new owner, usually the Crown.

Just about all mines now operate on the basis of progressive reclamation. But today, progressive reclamation usually means greening up large areas – it does not include building in final hydrology, water treatment for acid mine drainage, or reclamation of soft tailings sites. These expensive and technically challenging activities are left until a final decommissioning for the site. So while progressive reclamation is widely and successfully practised, most of the technically challenging items and those that have high unit costs are left until closure.

Despite reclamation at 51 of 69 mines which totalled nearly 21,000 hectares (the size of a prairie city), only two of the mines had *any* land certified and none had returned custodial transfer of any land back to the original owner.

The main reason for reclamation and progressive reclamation is to reduce liability. And, one of the main reasons for certification is approval of the land and transfer of at least some of the liability from the mine to the Crown. So the lack of land being certified is a major failure – the ultimate goal of reclamation is not being achieved. Not only is it a failure of the mine, but also of the regulators whose job is to ensure acceptable reclamation and return of the land. We are failing in our mantra of "temporary use of the land." The lack of certification and custodial transfer means that mining is a one-time use of the land and that once the mine is finished with the land, it hangs onto it indefinitely.

The lack of certified land suggests a "certification barrier." The reasons for this barrier are numerous:

- the goals for the landscape are poorly defined – it is unclear if the landscape is meeting the goals and neither the mine nor the regulators can be sure that the land will pass the certification test
- there is uncertainty regarding long-term landscape performance – both the mines and regulators are unsure that the landscape performance will continue to be good. No one wants to incur new liability if the landscape performance declines rapidly (for example, a large landscape, newly discovered seepage, or an extreme event such as a flood, wildfire, precipitation event, or earthquake)
- the value of the financial assurance posted by the mine is generally small and may be worth less than the risk of a re-evaluation of the bonding level or mechanism
- long-term maintenance is usually a thorny issue that avoiding certification avoids the issue of long-term maintenance.
- once certified, the land becomes off-limits to the mine for placement of further materials, drilling or exploration, roads, powerlines, or other infrastructure without a new permitting process
- there is little incentive for the mine to give up control of the land and even less for the government to take control
- liability for the certified land is uncertain. Polluter-pays legislation and the opportunity for other retroactive legislation means that the mine is at least partially if not wholly responsible for all future landscape performance. The regulator is unwilling to attract any or all of this liability
- failure of the land to achieve certification would have some dramatic effects
    - the mine and the regulators would both endure public embarrassment
    - the mine's liability for the rest of the landscape would increase (having had land that they thought was acceptable be turned down)
    - the mine's shareholder value may decrease
    - in most cases, a reclamation order is required to be issued. If the mine fulfils its order, the land must be certified. While it remains unfulfilled, mines may have difficulty (or it may

be legally impossible) to get extensions of operating licenses, expansion permits, or in some cases, start any new mining activities elsewhere in the country
- the mine management's bonuses may be affected.

Mines and regulators dwell on these issues and almost no land is certified. On the other hand, there is a lot of incentive for the mine to progressively certify the land since:

- progressive certification can be thought of as part and parcel with progressive reclamation and sustainable development
- some or most of the liability for the land is transferred to the Crown when the land is certified, and this can come off the mine's books. There is a large, though largely hidden, cost of carrying liability
- certification is a control point for the mine – it can be assured that its reclamation practices are acceptable, thus reducing the uncertainty in its liability
- stakeholders and shareholders likely view certification as a very positive feature and some consider certified land to be the only truly "reclaimed" land
- once land is certified, it is that much harder for "moving goalpost" regulations to affect it
- it assures that all the detailed (often costly) work is complete on the land
- it forces many of the issues of acceptable landscape performance and successful reclamation – reducing uncertainty for future reclamation and certification
- it reduces the mine's exposure to liability due to future extreme events
- management can be held accountable for certifying land
- financial assurance can be released
- the certification activity can be budgeted, staffed and tracked as a normal function of the reclamation department
- it seems to be the ethical conclusion to the promise of "temporary use of the land"

Certification is also a positive aspect for the regulators – they can point to a track record of certifying land, use the land certification as a test of regulations and a chance to reward mines that are doing good reclamation and point to it as a success towards mines that do less good reclamation or have no certified land. Quite simply, it is the regulators' job to regulate the mining and reclamation activities towards ultimate certification of the land.

Transalta's Highvale coal mine in Alberta is the only mine visited that has progressive certification. About one hundred hectares are disturbed, another hundred reclaimed, and another hundred certified every year. This process provides yearly progress and a demonstration of sustainable development. There is a permanent staff position that co-ordinates the paperwork and applications – it is fully integrated with the day-to-day operation and forms a model for the rest of the mining community. That the area is a strip mine and is being returned to simple agricultural use makes this mine perhaps one of the easiest to achieve this kind of conveyor-belt certification. That, however, should not detract from the incredible strides this company has made corporately and with the regulators to make this a reality. For mining to enjoy successful reclamation, this process has to start at all mines.

Secondly, there is a "custodial transfer" issue. Because the long-term liability for reclaimed land is poorly understood, mines are hesitant about turning control of the land over to the owner. It turns out that certification of the land does not usually imply that custodianship is also transferred – though on small sites this usually occurs right away.

None of the mines visited had any reclaimed land that had been turned back to the Crown, and indeed, though this is the number one goal, none is presently scheduled to be returned. More often, the mining area goes into dormancy.

Most mines recognize that they are liable for the sites forever. The mining landscapes are often fragile – re-mining, logging, or other disturbances to the site may trigger poor performance that may require the mine to repair. Thus mines are extremely hesitant to give up sites for which they are ultimately responsible, to unknown third parties or to the Crown. This "liability trap" means mines are on the hook forever and are justifiable unwilling to lose control over the site.

If there is long-term maintenance of the site required, mines are unwilling to give up control of the sites – damage by other users could increase maintenance costs. Vandalism and sabotage remain problems that mines try to control by controlling access to the site.

This long-term or perpetual liability for minesites may be one of the greatest issues facing the mining industry today – particularly for large mining companies with numerous properties.

As described above, due to federal polluter-pays legislation, the ever-present possibility of retroactive legislation, and a great deal of discretionary enforcement of hundreds of legislative items by regulators, mines have essentially unlimited liability for their sites. This liability is generally greatly reduced by certification and custodial transfer but significant amounts still remain.

Unlimited liability, by definition, cannot be quantified on the financial statements of a mining company. Indeed, liability for the landscapes is becoming an issue, but is generally undervalued. The trap is that as a mine buys or develops more mines, its liability continues to grow. As mines close, the operating revenues from new mines pay for the closure of old ones. But clearly, this requires an unending streak of new mines to perpetuate. But as a mine incurs more liability, its ability to attract new capital decreases and the mining company will eventually go broke.

With regard to financial assurance for reclamation and closure, the typical pattern for large mining companies is to pledge assets against its liabilities for reclamation and closure. As more of these assets are pledged, the mine must use alternative, more expensive sources of financial assurance such as bonding or insurance. Eventually, a mining company will not have enough assets or cash for bonding to pay for new mines or, in some cases, to continue mining old mines.

It should be noted that custodial transfer is common. Mines are often being sold to new mining companies and it is not uncommon for a mine to change hands several times during its life. Recently, there is an attempt to assess the liability of the site for the new owner but few likely recognize the extent of the liability they are buying into. In that past, owners of the mine (and indeed in many cases, the purchasers of the products of the mine) are joint and severally liability for future environmental costs at the site, even owning a non-producing mine for a short period of time can incur huge liabilities years down the road.

It should be noted that miners as a whole are an optimistic lot. Talk of liability and closure are usually the farthest from an operator's mind as a new mine is being opened. And the depth of the liability may not be apparent when a mine is in its main producing years, when it is seen as a benefit to the community and the regulators. But as mines go into the closure period, people start losing their jobs, and the economic benefits dwindle, there is a predictable track record of demands from the public and the regulators growing. Demands on reclamation and landscape performance increase dramatically. Often, it is seen as an opportunity for retribution against a far-away mining company with deep pockets. The changing regulations and liability for the site become dominant issues and stormy relationships are the norm.

So the certification barrier, custodial transfer barrier, and liability trap seen so clearly at the mines visited are the most significant long-term issues for mining companies today. Clearly a change in focus is required to make progressive certification a reality at every mine, making it part of the day to day business and setting up rewards for management and regulators for achieving progress in certifying more and more of the landscape.

New mechanisms that release a mining company from perpetual and unlimited liability are needed to maintain the health of the industry. Success indicators need to be established, met and certified as they occur. Closure planning is clearly key, especially its financial components.

4.5 Financial assurance

Much has been written on financial assurance for reclamation and closure costs, and requirements for bonding are growing both in size and use across North America. Financial assurance first started in the 1970s. At that time, bonding was based on a modest cost of greening up the landscape, offered in the form of corporate assurance (a pledging of assets), and was usually negotiated during development of the mine, often amounting to a small fraction of the final costs.

Mines entering perpetual maintenance in the past ten years have been asked to post corporate assurance to cover the cost of the annual perpetual maintenance. Assuming real investment rates of three to four percent (the long-term real risk-free cost of capital) and some taxation concerns, the it generally requires $30 to $100 of assurance for every dollar of annual maintenance. Lines of credit or bonding are often required. Mines can use capital dollars to invest in their closure landscapes to reduce annual maintenance costs and reduce bonding, but tens of millions of dollars of bonding upon closure are often required.

More recently, mines are being asked to provide assurance for the instantaneous cost of closure. Many mines close suddenly, and regulators want to have a pool of funds that can be used to reclaim the site if this happens. Often government union rates are used for estimation of the instantaneous cost of closure.

The instantaneous cost of closure for a large mine is often many times greater than the slow, progressive, considered reclamation and closure cost. For example, mining of certain rock overburden that will also be employed as a cover for a dump or placement of tailings sand hydraulically on soft tailings are two ways that a mine can accomplish its closure goals for almost no cost, if done in a planned and orderly manner during operation. In many cases, there is no economic method to achieve closure goals if mining is halted prematurely.

There are numerous articles on how to calculate the cost of closure and hence how to set the size of the financial assurance. Due to the inherent uncertainty, some propose the use of risk methods such as Monte Carlo analyses. But often, uncertainty in technology or goals swamp uncertainty in, say, unit costs. For large or complicated mines, closure costs can probably not be estimated to within 100 percent and, in some cases, perhaps even to within an order of magnitude.

Financial assurance is especially hard on small operators who may have few assets to pledge and who may have high unit costs for bonding. This gives an advantage to large mining companies. The advantage will perhaps be balanced by the fact that small mining companies may have less accumulated liability from other mining activities.

When large financial assurances are required from start-up, this takes away capital (or makes it harder to raise capital), makes mining less profitable and, in some cases, prevents development of new mines. Project economics may become dominated by levels of bonding.

Presently, bonding rates are negotiated with the government. Politicians may intervene, to direct regulators to require reduced rates of bonding or to accept corporate assurances instead of bonding in order to foster mining. Concerns for level playing fields and political interference may surface. Some areas are looking to legislate bonding formulas, mandatory means tests, and other less flexible methods. The result is that some mines that are too risky to tackle will rightfully not go ahead. But otherwise useful mines will not go, or become much less profitable and society as a whole may suffer. Even the delays caused by these processes may be enough to discourage mining and even exploration. Capital will flow elsewhere.

Clearly, mines have a track record of going bankrupt and leaving the government with huge expense to clean up the mines. Some level of financial assurance is required. But, seeing as society is the greatest benefactor from mining, it should accept some for the risk and levels of financial assurance should be carefully considered.

There is a new growth industry in bonding of mines. Also on the horizon is insurance for long-term performance or catastrophic failure. In the insurance industry lies a mechanism for an equitable transfer of liability. There is the potential for the government to negotiate with the mining company and the insurance underwriter a maximum limit for liability.

Liability, financial assurance, insurance – none of these captures the fancy of miners or reclamation specialists. It can become onerous and a bureaucratic nightmare, consuming time and resources, eroding competitive advantages of areas, and opening up abuse in other areas. But mining is ultimately about increasing shareholder wealth and increasing the wealth of society. These issues are presently out of control and new mechanisms equitable to all need to be created. Failure to do so may make mining a sunset industry in North America.

4.6 Elements of successful reclamation scorecard

Successful reclamation is not just greening up the landscape in a patchwork fashion. It is a complex activity that is much more than technical. This section defines the ten elements of successful reclamation, and provides a scorecard of where the Canadian mining industry sits today. While advanced in technical areas, there is a long way to go to improve our scorecard on other elements. Fortunately, with management attention and dedication, the other areas could be improved fairly easily.

- **Management support**

The support of management, from the mine manager to the president, is critical. Management cannot just pay lip service to this effort. They must be willing to actively support the work, supply the budget and staff and intervene if necessary.

- **Stakeholder involvement**

A critical element is to work with stakeholders – local groups and communities affected by decisions and who have an interest in the operation. This takes a great deal of work and integrity to act on the information and preferences of these stakeholders. Having the assistance of an effective public consultation consultant in the beginning is often a good idea. Management buy-in to this element is critical.

- **Communication**

Communication of plans and successes to stakeholders, including employees, while avoiding overselling is essential. One must ensure the methods of communication used are suitable to the audience – aerial photographs or paintings can be useful tools in communicating existing operations or an end vision. Few stakeholders are good at reading maps. Be truthful in your communications and include information relating to uncertainties. In the oil sands industry, one of the messages communicated is that, presently, we do not have the know-how to reclaim every area but we do have credible and concurrent research and development programs to get there.

- **Planning**

Good planning is essential. Ensure you are on the closure path – generating periodic realistic closure plans, progressive reclamation, and other things needed to bring the area to an orderly closure. Get the closure costs into the feasibility assessment.

- **Economics and decision making**

Throughout the process a number of questions must be answered such as how are decisions made about reclamation, how are choices made between alternatives and how are the benefits of reclamation valued? Using a corporate economic model with discount rates or return on investment hurdle rates of 20 percent will give you the wrong answer.

We need to realize that every dollar spent on reclamation is a dollar of foregone profit, and that means royalties and taxes paid to governments are reduced. In Alberta, this means the government or public is paying 60 percent of every reclamation dollar spent. As taxpayers, we need to ensure reclamation dollars are spent wisely.

- **Research and development**

These two elements are also critical to success. The research must be done and the results translated into designs to be carried out by the operation. For complex sites, 10 to 20 percent of the reclamation budget may be going into research.

- **Technical and operational know-how**

This is the nuts and bolts of planning and executing reclamation and getting it done efficiently at full scale in the field. When we set our minds to it, we surpass expectations.

- **Landscape performance**

Having performance that meets predefined goals (worked out with input from stakeholders and regulators) is key. Currently, the industry is experiencing some success in this area.

- **Risk management**

This element means monitoring sites and having viable contingencies in the event performance fails to meet goals. Too often, reclamation is done with no margins for error, no multiple lines of defence and no allowances for defects.

- **Independent audit**

It is important to obtain an independent, third-party review of reclamation to ensure it is meeting the agreed-upon goals.

In a cross-Canada workshop held in May 1999, ten participants from the Canadian mining industry rated each of the above elements to determine how the industry is doing in terms of achieving successful reclamation. See Table 4.4 for the results. Participants were asked to rate the elements as high (H) performance, medium (M) performance, or low (L) performance. High performance means that there are effective systems in place and being used. Medium means that attempts are being made with mixed results. Low means that either there are no systems or the results are poor.

The results show that we are likely not achieving successful reclamation. While we do enjoy success on the strength of research and development, technical know-how and landscape performance, it is clear that improvement is needed in a number of other areas. This is especially true in an era of ever-moving goal posts and continually increasing expectations. It need not cost more in the field, but a change in the level of design and technical work is certainly needed. The changes required are essentially a change in management focus. Failure to change means the mining industry will continue to struggle in achieving its ultimate reclamation goal of reduced long-term liability and return of the land to a willing custodian.

Plate 4.1 Two uraniferous tailings sand beaches direct seeded and performing well as natural and recreational areas.

Plate 4.2 **Two tailings sand beach plateaus successfully reclaimed as pastures for bison and cattle.**

Plate 4.3 A tailings sand slope showing initial signs of rilling and gullying. (Tree-stumps on waste rock dump in foreground are snags for raptors). The lower photo shows a sparsely vegetated and actively eroding tailings dam slope.

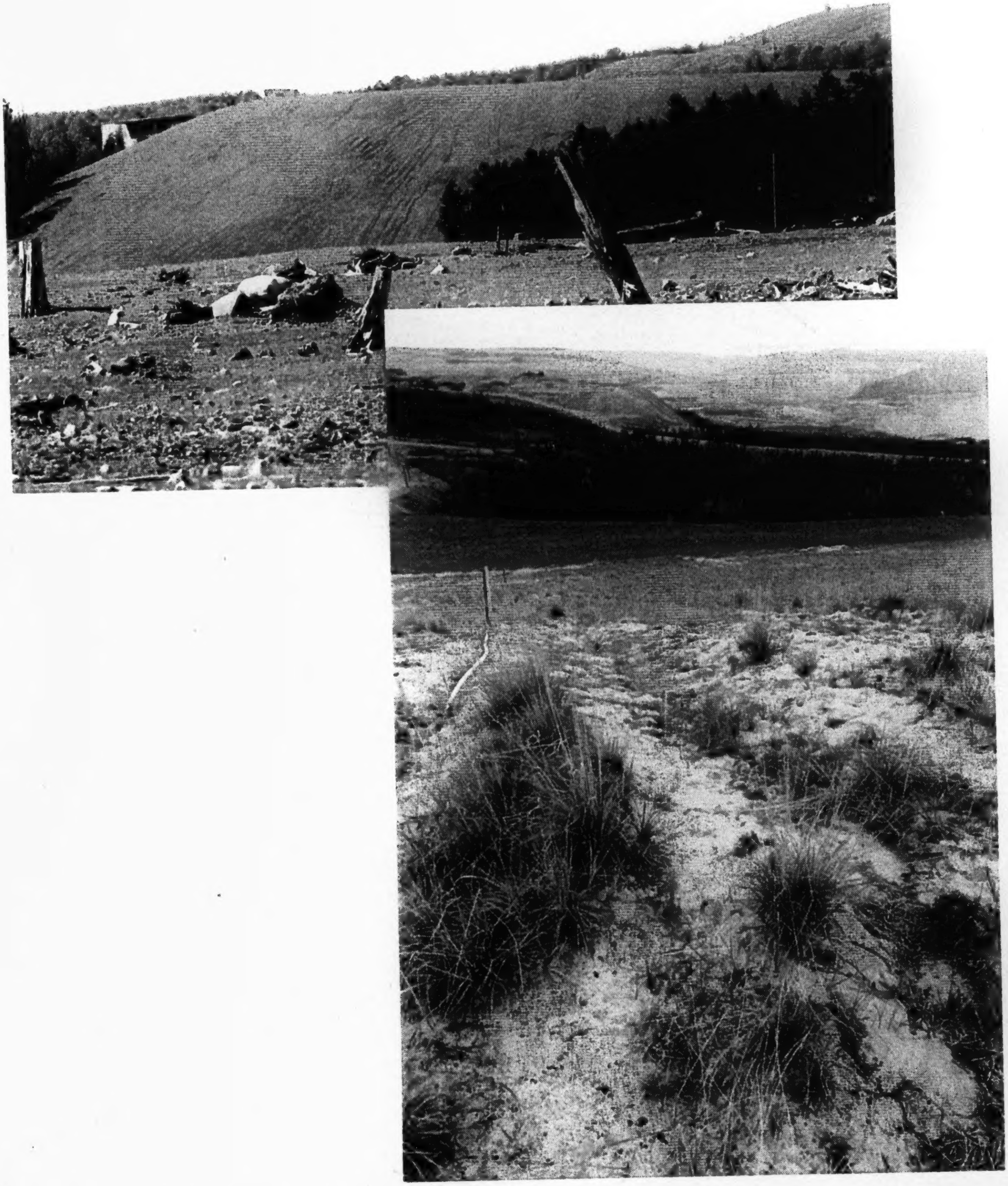

Plate 4.4 **Two sparsely vegetated and eroding tailings sand slopes.**

Plate 4.5 Marginal (perhaps just early) landscape performance of a resloped dump.

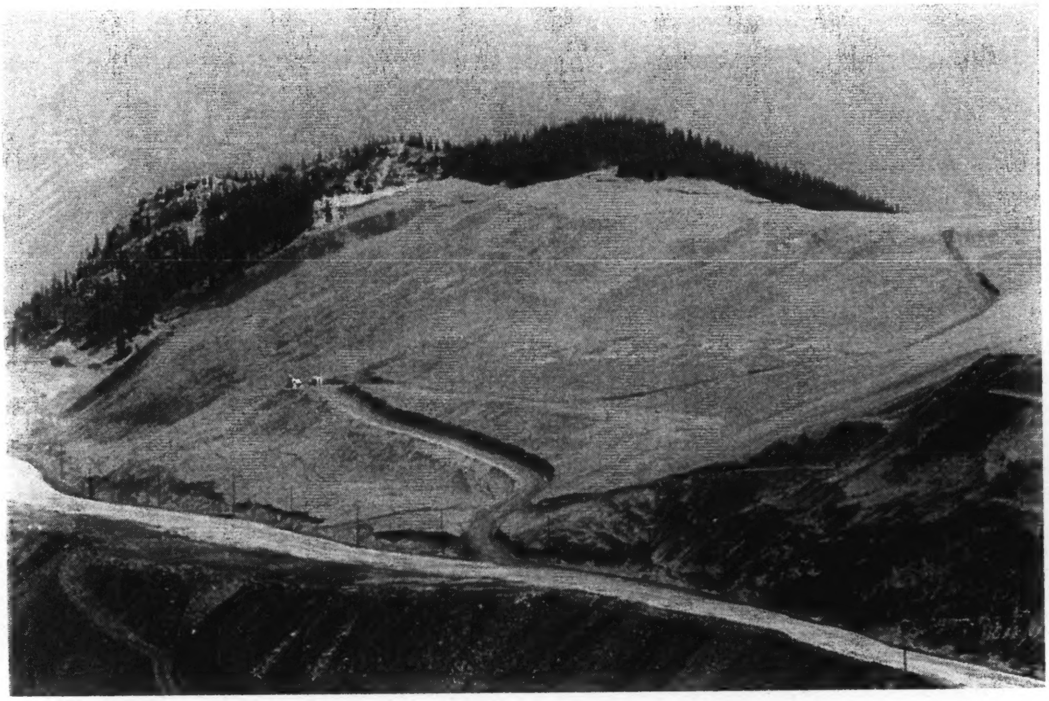

Plate 4.6 High-quality reclamation with a gravelled footpath. Benches and interpretive signs kindly provided for walkers.

Plate 4.7 End-pit lake, just before final ocean inundation.

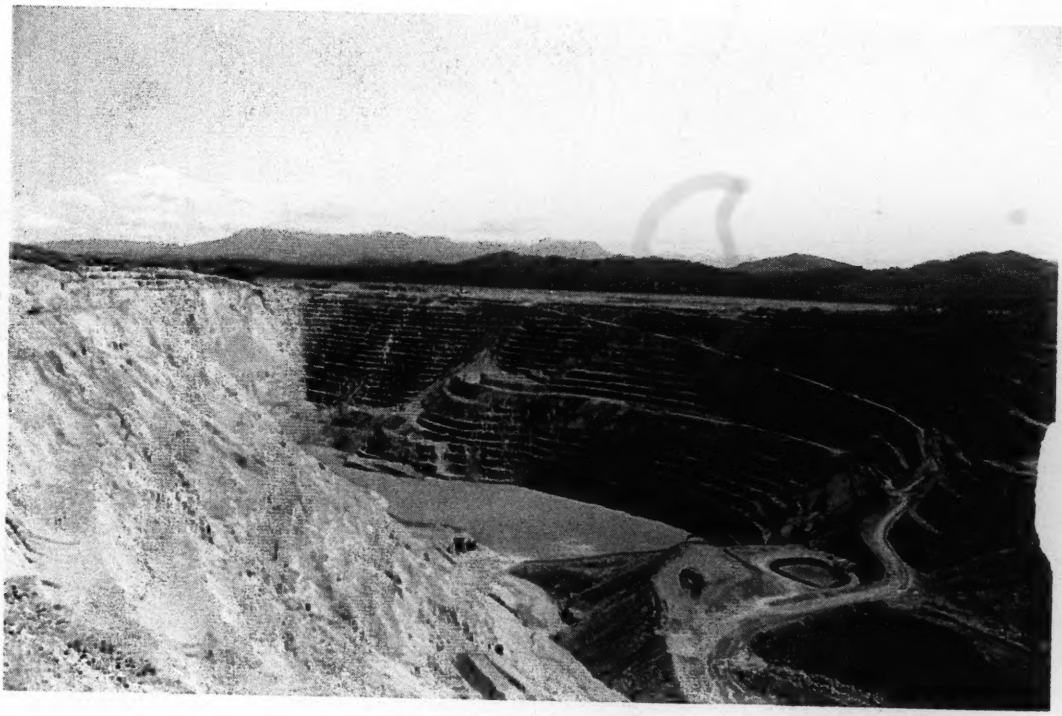

Plate 4.8 The author's favourite spot during the mine visits – an end-pit lake (which incidentally never reached full height) in the Rockies. Perfect for a retirement cabin.

Plate 4.9 Tens of millions of dollars were spent reclaiming this site, but to little benefit. The site will be permanently fenced off due to concerns about selenium and radioactivity, not to mention lack of vegetation.

Plate 4.10 **Two end pit lakes**

Plate 4.11 An end pit lake filling five times faster than expected

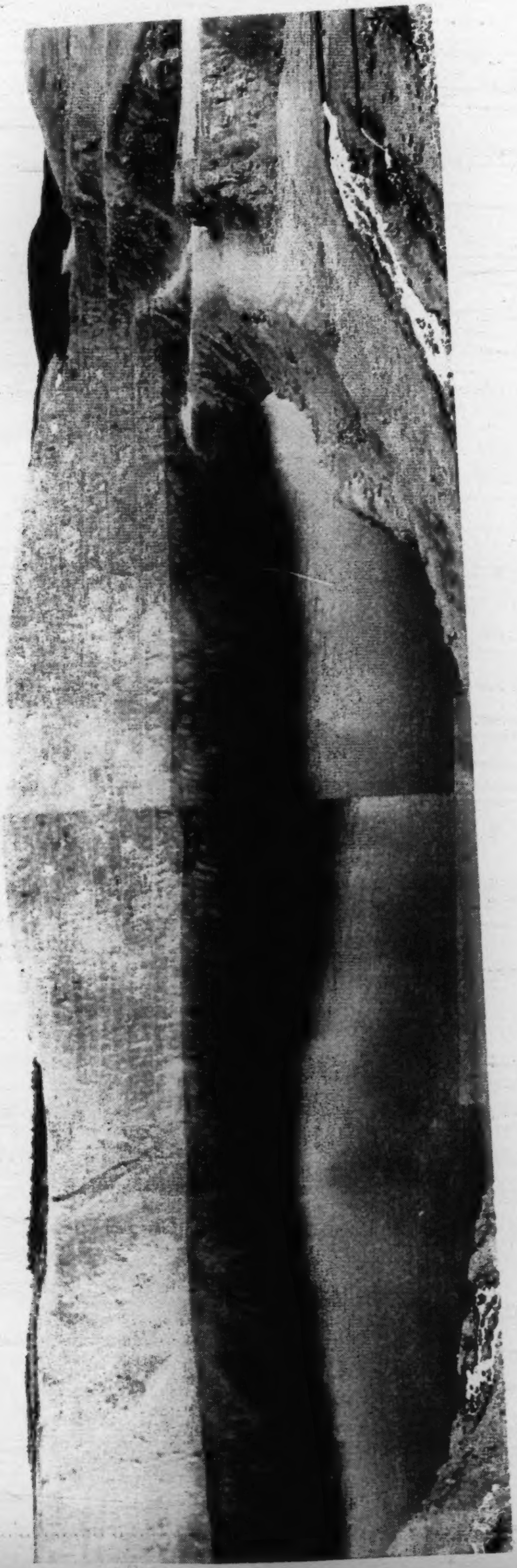

Plate 4.12 Burying radioactive waste with less radioactive dirt

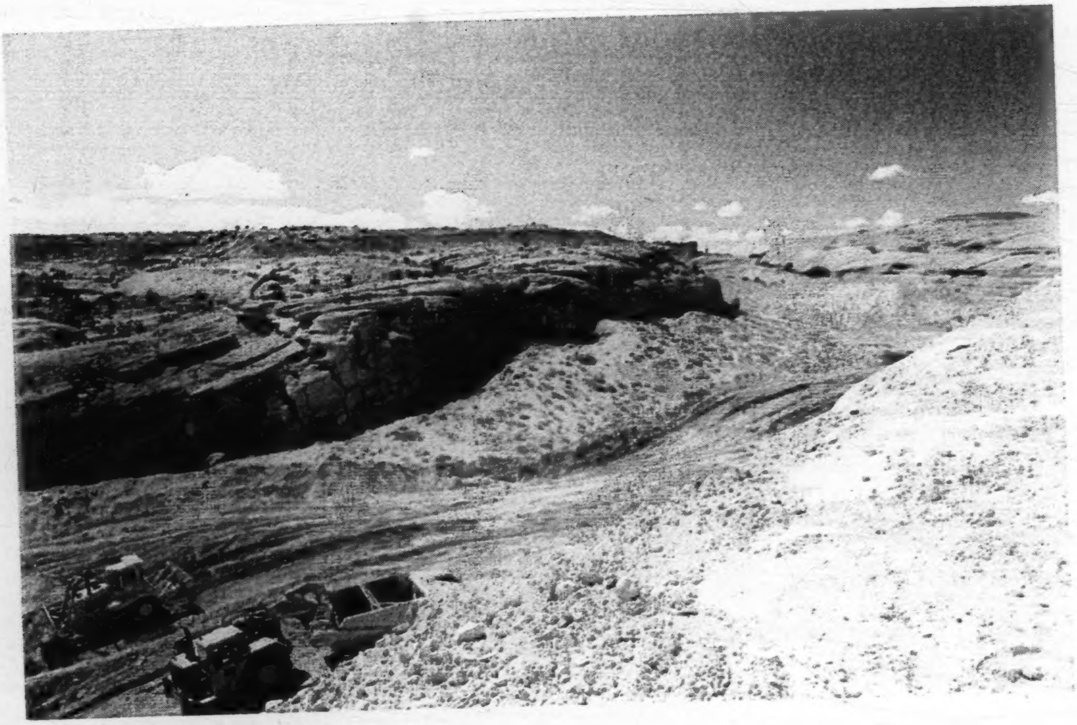

Plate 4.13 Badlands reclamation: when nothing will grow, add rock for colour

Plate 4.14 **Successful reclamation in a semi arid region**

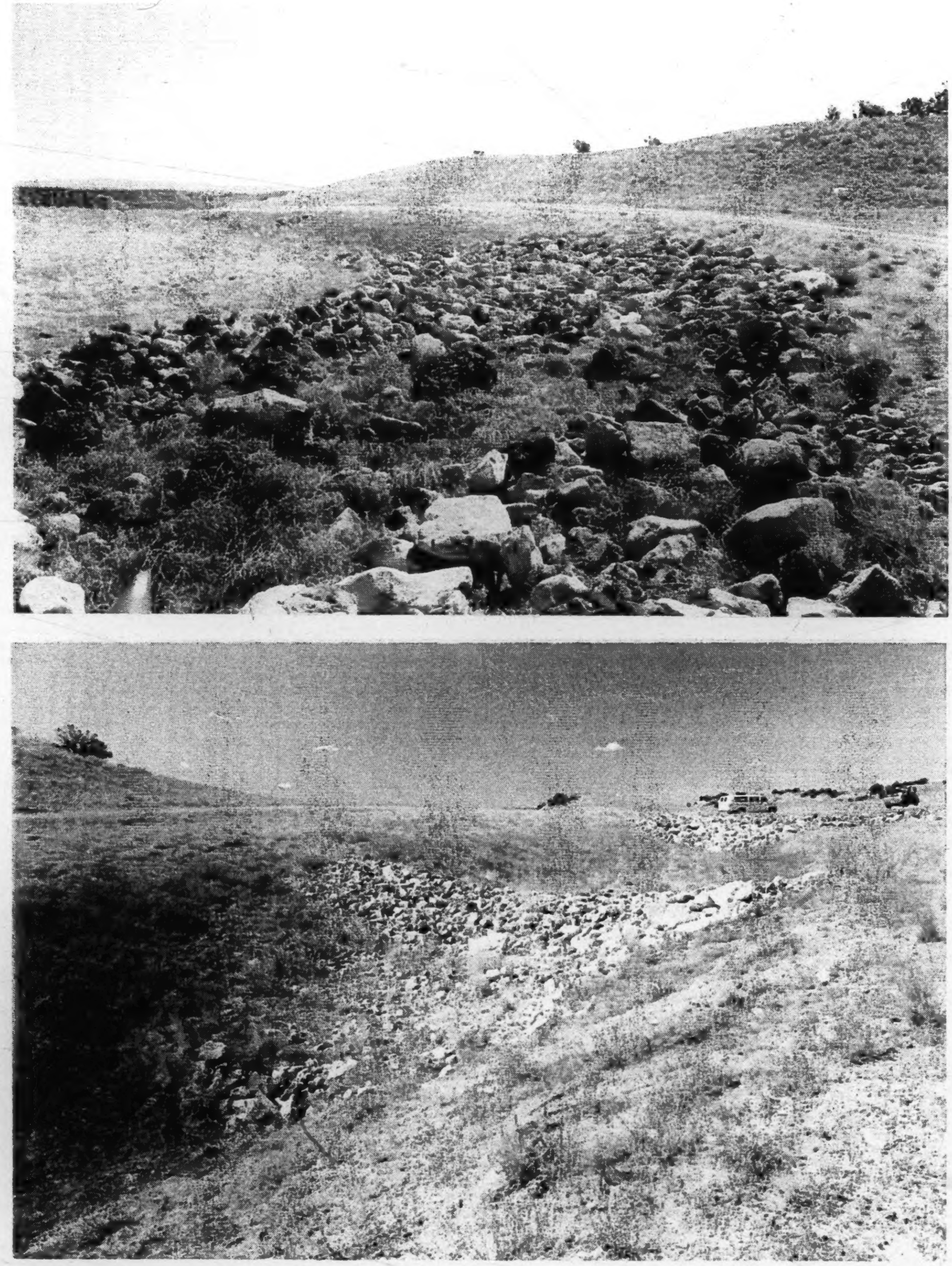

Plate 4.15 Waste rock sculpted to provide embayments for fish

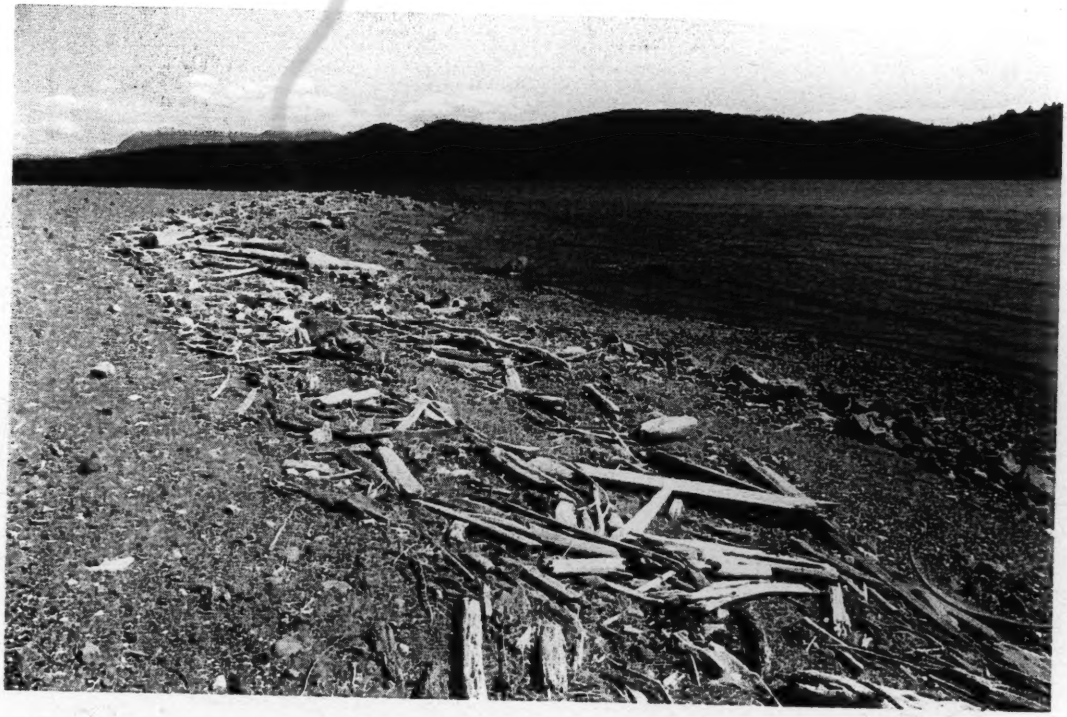

Plate 4.16 Reclaimed shaft and millsite

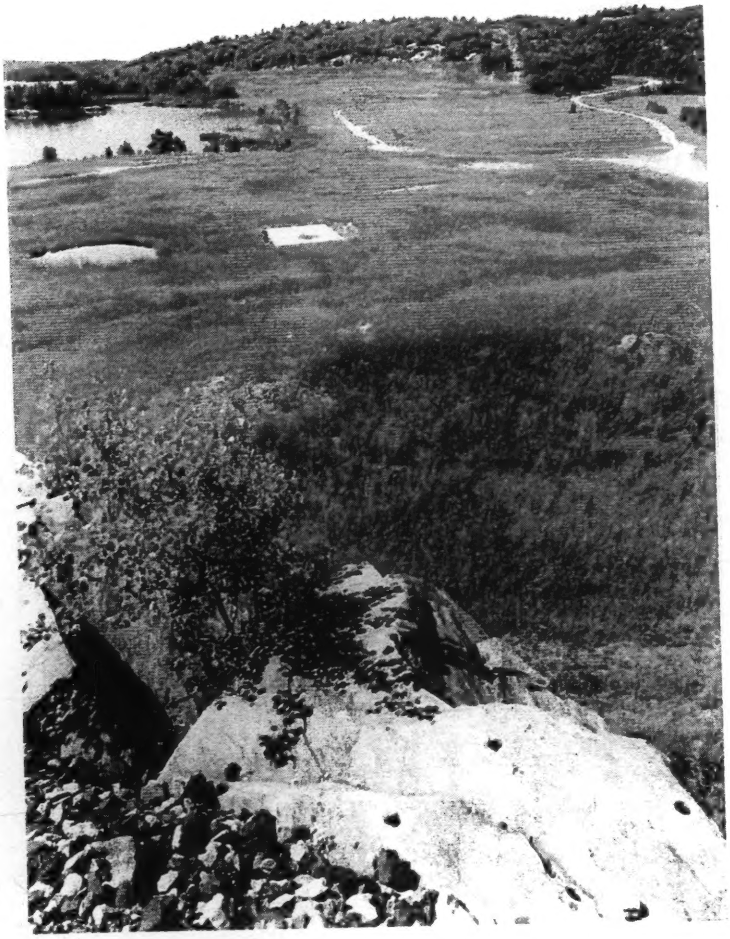

Plate 4.17 Innovated practices: information kiosk (above) and slash placed on reclaimed dump (below)

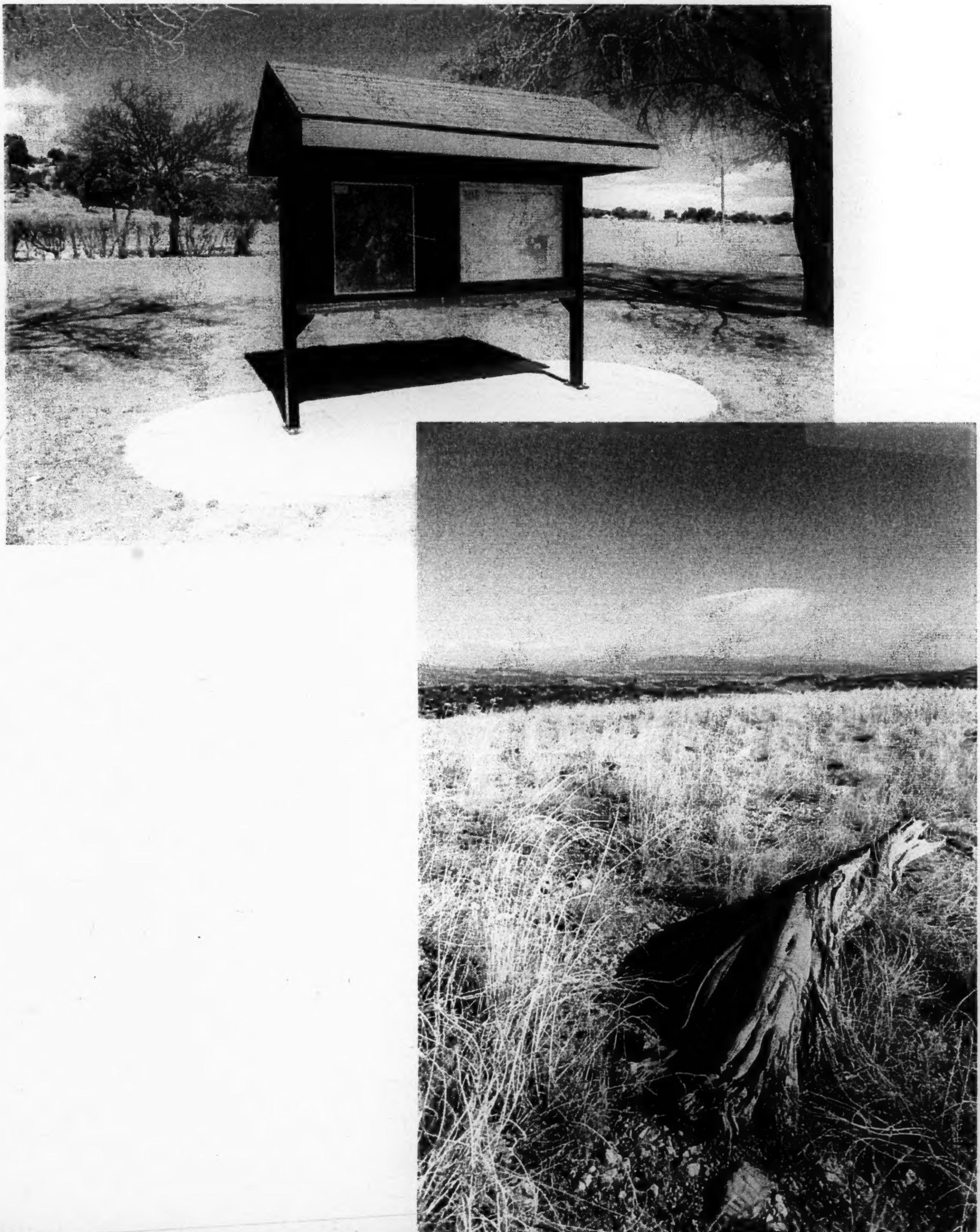

Table 4.1 **Performance of pitwalls**

Pitwalls that will be resloped or buttressed		**Pitwalls that are active (spalling and or landsliding)**	
Radiant York Canyon Lee Ranch McKinley AML 902 AML 907 Monument Valley 2	Castleridge SF Phosphate Line Creek Syncrude Mildred Lake Syncrude Aurora Suncor	Jackpile Island Copper Highland Valley Copper Brenda Golden Gravel Equity Silver Bell Granisle	Tent Mountain Greenhills Falconbridge Inco Sudbury Gravel Bitumount Alsands Whitewood
Soft rock pitwalls are sometimes reclaimable.		*Hard rock pitwalls are seldom reclaimable.*	

Table 4.2 Performance of end-pit lake filling

Mine	Performance	Reason	Impact
Lee Ranch	Filling slower than expected		
Brenda Mine	Pit filled 4x faster than predicted	Incomplete surface water balance	Water treatment plant cost advanced by 15 years
Gibraltar Mine	Pit filling several times faster than expected	Did not fully consider groundwater discharge rates	Advance need for water treatment if mine doesn't reopen
Equity Silver	Pit filling 2x faster than predicted		Affects water treatments and sludge disposal plans
Island Copper	Filling 2-4x faster than expected	Filling channel to sea over excavated?	None
Greenhills Coal	Okay, but no schedule predicted		Pit filling schedule not important to operation
Bell Mine	Pit filling on schedule	Small islands of known watershed side	
Granisle			
Highland Valley Copper	Trojan Pit filled to higher elevation than predicted		Destroyed planned littoral zone, no fish
Tent Mountain	Pit filled to lower elevation than predicted		Outflow inactive (probably good)
Quarry Lake	Final elevation seems okay		
Ohio State University	Elevation and flow rates carefully controlled	If not controlled, poor predictability recognized	Active monitoring
Syncrude	Tailings substrate in lake densifying much faster than predicted	Uncertainties in mechanisms and predictions, new mechanisms	Affects tailings volumes and may affect future environmental performance of lake
Summary	Pit filling usually faster than expected and final elevation mispredicted	Poor understanding of site water balance, failure to take a more conservative approach	Planning, economics, and intended land uses are often severely affected

Table 4.3 Summary of landscape performance observations

Landform	Typical performance	Issues in planning and design	Issues in construction	Issues for maintenance
Tailings slopes	Generally poor vegetative and erosion performance; almost impossible to reclaim	✓		✓
Tailings beach areas	Good			
Soft tailings	Untrafficable, subsidence issues	✓	✓	✓
Dumps – at repose	Good			
Dumps - resloped	Good but overland flow needs to be addressed	✓	✓	✓
Dumps – level	Good but need to prevent overtopping and subsidence puddles	✓	✓	
Dumps – engineered / capped	Good but improved predictability of percolation and long term maintenance requirements	✓		✓
Chemical contaminants	Not carefully enough considered	✓		✓
Pitwalls	Either buttressed or resloped where practical or mandated. Otherwise, acceptable levels of spalling and geotechnical instability common.			
End-of-pit lakes	Almost impossible to predict filling rate, long-term levels, long-term performance. Needs more effort and research and a more conservative approach.	✓	✓	✓
Rivers and creeks	Almost never designed, when designed, construction does not follow plans, long-term stability in doubt.	✓	✓	✓
Shafts and portals	Generally excellent, except where trespassers destroy or bypass them.			✓
Fences and infrastructure	Generally good, but requires maintenance.			✓

Table 4.4 Ratings for successful reclamation in Canada

Reclamation element	Scored by workshop participants	This study	Comments
Management support	L	M	Workers generally feel low levels of management support, but managers feel they are providing high level of support
Stakeholder involvement	L	M	A few mines have successful stakeholder programs, many have none
Communication	L	L	In general, there is poor communication to staff and stakeholders about reclamation efforts and decisions
Closure planning	M	M	Many mines have effective closure planning systems, many have none
Economics and decision making	L	L	Few mines have rational methods for deciding the amount and timing of reclamation expenditures
Research and development	M	M	Some mines have a lot of useful research, many have none
Operational and technical know-how	H	M	Most mine have a good ability to green up large areas, but few are proficient at the finer details
Landscape performance	M	M	Landscape performance is generally quite good, but few areas have been tested by extreme events
Risk management	L	L	Few mines consider risk or long-term performance
Independent audit	L	L	Few mines use any auditing system
Note: H = high, M = medium, L = low			

5.0 FINDINGS: CHALLENGES AND NOVEL CONCEPTS

5.1 Closure planning and reclamation challenges

For mines and the regulators, the challenges to reclamation and closure planning are daunting. This section provides a broad overview of the major elements.

- **Challenges in design and planning**

The absence of a clear methodology or framework of defining goals and designing to meet these goals is the greatest challenge in design and planning. It is further complicated by the large tracks of disturbed area that are already reclaimed or disturbed in ways that make achieving retroactive goals difficult. Perhaps the greatest deficiency in the present framework is a method for dealing with the uncertainty of long-term performance. This is one of the major contributors to the certification and custodial transfer barriers.

- **Reclamation operation and construction**

Actual reclamation operation and construction is a relatively mature area and so has overcome most of the earlier challenges. The greatest challenge facing this area is becoming efficient at the finer details of reclamation – finishing up the bulk reclamation with repairs to bare areas, constructing streams, and ensuring the final finishing touches are taken care of. Adopting the dualism of cheap bulk reclamation with careful finishing reclamation is a significant challenge.

- **Monitoring and maintenance**

The challenge of monitoring and maintenance is to get a system started that can gather and manage the data. This requires a special dedication of a few staff members. Designing a program that collects the right data at the right frequency, then a management system that allows the mine to act on this data is critical. Filling the gap for the lack of historical data or even inputting the historical data into the data management system is often overwhelming.

- **Financial**

Financial challenges are perhaps the greatest faced by mines. Most of these centre around the lack of understanding regarding long-term liability. Once this liability is better recognized, the key challenges are to manage reclamation costs throughout the life of a project, to try to avoid escalation of closure costs due to changing regulations, and to set up conditions for the closure period that will permit efficient closure.

Perhaps the most pressing challenge is to address the dormancy strategy to which so many mines default. There needs to be better management of costs and financial instruments in the closure period so that the mines have the resources and desire to finish reclaiming their sites and turn them back to the original owner. Financial assurance is a tool being widely employed but will probably not be that successful in achieving the landscape goals.

- **Cultural**

Cultural challenges relating to closure focus around the need to work closely with local stakeholders to understand the goals and desired land uses for the reclaimed sites. The conflict in the goals of regulators, stakeholders and miners needs to be resolved early on, allowing all parties to work closely towards common goals.

One of the major mechanisms for poor performance of reclaimed landscapes is abuse by the local community after closure – vandalism, inappropriate land use, and lack of care and attention. The local community needs to understand their roles and responsibility as users of the landscape to contribute to its ongoing performance.

- **Regulatory**

The challenges faced by mines relative to regulatory interaction are considerable and most come down to the lack of clear and achievable goals. Again the solution depends on a good framework for setting and achieving goals. Attempting to mandate good performance through regulation or prescriptive goals has much less chance of working compared to establishing a few key objectives and working together over the mine's life to achieve them.

There also needs to be a mechanism to accept moving goal posts. It is unreasonable to think that regulations, expectations and learnings won't change over the life of a mine, especially in that most mines operate over decades and many over a century or more. But there needs to be a mechanism to shield mines from ever changing regulations and changes that are too severe or unneeded.

- **Physical**

Challenges that relate to the physical performance of the landscape centre around planning and technical issues. The physical performance goals need to be better framed and specific methodologies to achieve them on a technical level need to be both understood and employed. The most glaring shortcoming is the poor understanding and implementation of surface water hydrology.

- **Chemical**

Challenges related to chemical stability of landscapes are most often experienced by mines with acid mine drainage and, indeed, a whole knowledge base and industry has evolved to meet this challenge. The major challenge is that, through mining activities, mines create landscapes that are especially prone to chemical migration and change and the costs to remediate the reactions and migrations is very high. Clearly, better planning from the start can help to reduce costs, and it is already recognized that mitigation in any case is expensive.

- **Land use**

The greatest challenge in land use is setting and achieving land use targets in a sustainable manner. The land uses must be chosen carefully and realistically and, once they have been agreed upon, mines need to work hard to achieve them.

- **Biological**

Biologic challenges have been addressed and many resolved over the past several decades. Major challenges now are moving to more ecosystem-based approaches and the exclusive use of native vegetation required in some jurisdictions. Understanding how successional changes in vegetation and wildlife affect the landscape will remain challenges well into the future. We probably need to take a step back and recognize that the changes are inevitable and not entirely predictable and design the landscapes with this in mind.

- **Complexity of landscapes**

Landscapes are complex systems and are subject to perpetual and extreme internal (intrinsic) and external forces. Prediction of their future behaviour is difficult at all but the most simplistic levels. A full understanding of the intricacies and mechanisms behind dynamic landscape performance is impossible. A modest understanding may not be practical either.

The result is we need to avoid promising that the landscape will perform in certain ways, unless we are willing to control its evolution through management inputs (long-term monitoring and maintenance). We must take steps to understand the basic mechanisms and bring them into our design practices, and chose design practices that are somewhat forgiving of our ignorance.

- **Complexity of mine/regulatory relationships**

It is not only the physical landscape that is complex but also the system of goals, regulations, legislation and personal interaction that go into building and judging a landscape.

Steps to simplification are needed. Moving towards a purely prescriptive approach ignores the reality of landscape complexity and is doomed to provide poor results at all but the simplest of sites. Instead, we need to provide mechanisms to use judgement and be accepting of best efforts.

- **Summary**

Mines and regulators have created most of the challenges faced in mine reclamation. The realization of the complexity of landscape performance and the uncertainty about long-term performance have come after most of the institutions, mechanisms and agreements were put in place. We scramble now to adapt the existing framework to accommodate new understandings. The certification barrier, custodial transfer barrier and liability trap are all outcomes of this clash.

Most of the technical issues are resolvable, providing that we don't ask or offer too much in terms of landscape performance. A new framework to accommodate this new approach is required, and is perhaps available through landscape engineering.

The solution to most of these challenges is close co-operation between mines, regulators and stakeholders. Achievable goals need to be set out clearly and all need to work towards achieving these goals. The point of regulatory control needs to be shifted away from meeting prescriptive criteria and providing assurances of long-term performance based on models, and moved towards creating reasonable designs, having them approved, and following through on these designs in field construction. This new framework short-circuits most of the challenges and provides measurable performance goals for the mines and regulators.

There also needs to be a fundamental change in the way liability is addressed and assigned. Long-term liability of mines for future landscape performance will cripple the industry over time. Issues of liability are not limited to the mining industry but reflect a society view. Whether meaningful changes can be made remains uncertain.

5.2 Novel concepts and innovations

Table 5.1 and Supplement B list a series of novel concepts that were provided by the mines, communicated by the person providing the tour or observed on the visit. In that most of these novel concepts are invented by individuals or groups at individual mines, extracting themes from the checklist is difficult. Instead, the checklist is provided to offer a shopping list of things that can be adopted. Table 5.1 shows a summary of where the major innovations are occurring.

Plate 5.1 Historical buildings from a bygone era at a dormant colliery.

Table 5.1 Focus of innovative work regarding closure planning, landscape design and reclamation

Area	**General focus of recent innovations**
Design and planning	Developing methods and rationales for the work that satisfies management, regulators and stakeholders
Reclamation construction	Developing methods for better placement of materials, using one-time placement
Monitoring and maintenance	Developing rational methods for acquiring and storing and communicating data
Financial	Rationalizing how much reclamation should cost and how well they can or can't be estimated
Cultural	Completing activities that can make the reclaimed landscape more appealing to stakeholders (through improvement and involvement)
Regulatory	Effort is focussed on trying to change regulatory processes
Physical	Ideas for landscape design and planning that create more stable landscape, mostly through managing surface water and groundwater
Chemical	Most of the innovations of interest focus on identifying problems and problem materials before mining starts, mainly centred around acid rock drainage
Biological	This has two main areas of focus – refinements of revegetation practices to reduce costs and innovative methods of creating improved wildlife habitat

6.0 SOLUTIONS

It is becoming increasingly clear to many mines and regulators around the world that closure planning is a valuable activity. It is also clear, however, that we do not presently have all the tools to ensure that mines can reliably meet their closure goals. The existing model of greening up static landscapes does not provide the required framework.

Clearly, a different level of activity is required in the setting of goals, designing and constructing the landscape, and assessing its performance. Goals cannot be made up nor agreed to without proper consideration of their achievability. The landscape cannot be constructed with the simple instructions of a mine manager standing in the field, nor by considering individual landforms or individual sciences separately. Questions of long-term maintenance cannot be left until the landscape is largely constructed. Questions of long-term liability need to be settled before mining begins, not after it has ceased.

What is needed is a more integrated approach – an integration of goal setting, design and construction and landscape elements. A framework is required that encompasses each of these items and allows the various specialists to work together to provide designs and landscapes that come with a reasonable assurance of meeting the agreed upon goals economically. In the process, the specialists will provide a landscape that will have continuing usefulness to humans.

Landscape engineering is proposed as an umbrella discipline for creating sustainable landscapes. It provides an engineering focus to create landscapes that meet specific goals. It also provides a multidisciplinary approach that integrates mine planning, operation and reclamation. In particular, it allows a rational framework for designing landforms and substrates and for selecting vegetation.

With landscape engineering helping to lead the way in closure planning, there will be a change of focus in a number of areas.

First, there will be a change in focus in mine reclamation – a change from revegetation to designing, constructing and monitoring integrated landscapes.

Second, to date, mine reclamation has been dominated by biologists. We need to build on their expertise to focus on physical aspects as well.

Third, we need to break from the paradigm of individuals going it alone and start to work more in multidisciplinary teams.

Fourth, we'll change from a focus on greening up the landscape to certification and ultimately, to what really counts – the ultimate transfer of custodianship of the land.

And, finally, we need to build on the science of reclamation and change it to a combined scientific and engineering focus, bringing to bear the tools available to engineers and meshing these will the skills of the biologists and other scientists. The overall focus will be on reaching the mine management and financial community in ways that they can also understand.

Landscape engineering offers a new framework but in itself will not be enough. Mines need to focus on all the elements of successful reclamation and work towards improving their own scorecard and that of the industry as a whole.

But even given improvements in all of these areas, the most daunting of all is the need for a societal change. The general belief that societies can flourish without primary resource industries such as mining will historically be considered as one of the greatest mistakes of the current era (Homer Dixon, 2000). Society needs to embrace or reaffirm the need for resource industries, and be willing to accept the landscape changes that these bring about. But even more than this, society needs to re-examine how it accepts long-term liability of events that are outside its control. We accept that the natural landscape changes, but are unwilling to accept liability for the changes that occur in reclaimed landscape. Until we can resolve the issues of liability and, in particular, methods of limiting long-term liability for mines for their activities for which society has benefited and prospered, mining will be unable to fulfil its promise of temporary use of the land, and the mining industry will continue to decline.

But at some future time, society will better recognize the value and importance of mining (to local, regional, and national economies and sovereignty) and it will takes steps to foster the mining industry. Better institutions for determining, accepting, transferring and limiting liability will emerge out of necessity. Additional costs for reclamation and closure will only marginally affect commodity prices. The key then is to recognize the shortcomings in present systems and start the transition to a more workable system. The challenge is great. This study has focussed on the positive and positively challenging aspects – technical, financial, and societal. The companion report on landscape engineering provides a new framework – perhaps a significant step in the transition to where mines will be able to properly fulfil the mantra of temporary use of the land, and create new useful landscapes for society.

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The following sources of information were used in the compilation of this report. While they are not always explicitly referenced in the text, they are intended to provide the reader with additional sources of information. In general, there is very little published about specific mines, much less their reclamation practices.

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Supplement A
Compendium of goals

This supplement captures all the goals as stated at the 69 mines. Table 3.1 and Figures 3.5 and 3.6 provide summaries of this supplement.

Financial

- **Avoid impacting other company mines by having a violation**
  Some companies will avoid seeking their bond money back because if denied (via a violation) they may be prohibited from opening up any new mines anywhere in the U.S. until the violation order is removed.
- **Bond release**
  The number one goal of most mines seems to be to get its reclamation bond back by meeting regulatory requirements. This also discharges many of the mines long-term liabilities.
- **Bond roll over**
  Some companies seek not final release of the bond but approval of some areas of reclamation areas so that new areas can be opened up without new funding required for bonding. Conversely, some companies seek to turn the land over all at once arguing that to turn it over bit by bit is too much effort in dealing with the regulators.
- **Create maintenance-free landscape**
  More than a few mines hope to be able to reclaim to the point where they can walk away from a maintenance-free site without liability. In this way, they will create a landscape that can continue to function as promised without maintenance or intervention.
- **Future re-mining**
  Many mines see the potential of remaining previous spoil piles with new technology or higher prices. Some also consider continuing to mine ores with higher and higher stripping ratios. They would like to leave the site with the potential of future mining or re-mining. Reclamation and closure continues, but with a mind to re-mining.
- **Have same closure goals as sister mine nearby**
  Some mines have goals that are in harmony with a nearby project owned by the same company.
- **Keep minesite in dormant state**
  Many mines wish no more than to hold onto the land, doing the minimum required to keep it ready for resale, often for the reserves left in the pitwalls or for commodity prices to recover. In some cases, in particular gold tailings re-mining, it would be disadvantageous to reclaim the site (beyond physical stability) as it would make re-mining costs more expensive. Sometimes, mines may be waiting for new technology to be developed. Dormancy is perhaps sometime an excuse for not starting closure reclamation.

- **Keep mine open for future mining (no cover reclamation)**
  Some mines are thought to be in temporary shutdown so may want to provide no cash into the program and would like to leave things as they are so no unneeded reclamation would be done.
- **Minimize closure costs**
  Few mines say outright that their goal is to minimize closure costs, perhaps because it is generally understood.
- **Minimize monitoring and maintenance timeframe**
  Some mines minimize post-closure monitoring costs and the timeframe for monitoring or restrict it to a specific time frame (say three years or 150 years).
- **Minimize post-closure monitoring costs and monitoring time period**
  A few mines have specific objectives for monitoring costs and timeframes and work to minimize these.
- **Negotiating tool**
  For some mines, reclamation is a negotiation tool. They may offer more reclamation in turn for getting new mining approved. Conversely, the regulators may require more reclamation before approving new mines.
- **Public relations for mining company, government, stakeholders**
  For those companies that advertise or promote their mines, the foremost sales job is done on the reclamation. Reclamation then is often done with a mind to promote the company, the land owner, the fixer-upper or the government regulators.
- **Recapitalizing next economy**
  This is a goal to create a useful landscape to stimulate economic revival.
- **Reduce liability**
  Few mines realize that the number one goal of closure and reclamation is to reduce liability.
- **Reduce long-term maintenance costs**
  Long-term maintenance costs can be reduced through capital investment into covers and robust design to create a pumping system that requires very little maintenance and could be monitored by computer offsite. In some cases, this is expressed as having only a small amount of annual maintenance to the landscape to repair erosional features
- **Return of land to original landowner**
  After bond release, the land goes back to the original land owner, and this may occur before bond release as well. If the mining company owns the land, it will seek to sell the land to a new land owner.
- **Satisfy stakeholders**
  One of the main goals of reclamation is to meet the needs of stakeholders – partly as a strategy to do what the public wants and partly to pave the way for continued or better relations. Demonstration of stakeholder satisfaction is sometimes a regulatory requirement.
- **Sell buildings and equipment**
  One of the goals during closure is to sell buildings, facility, the land or used equipment.

- **Store water for as long as possible**

  Many mines use their mined-out pit to store water to avoid having to build and operate a water treatment plant for some decades (taking advantage of the time value of money).
- **To reduce levels (flux) of acid rain drainage (ARD) required for treatment**

  Reclamation at some mines aims to reduce the percolation of water into acid waste rock to reduce the volume of acidic water that needs to be treated each year. The economics of this situation are easy to calculate – the trade-off between early capital in creating infiltration barriers versus the reduced long-term costs of water treatment. Often a good strategy is to keep the trees from growing on an infiltration barrier as these can cause percolation rates to increase.
- **Tourism**

  Some sites, particularly older mining sites, have tourism value and reclamation of these waste sites is usually avoided. People may also seek to create museums as part of the site reclamation showing original spoils and old mining equipment, and in some cases, offer underground mining tours or even tours of the reclamation.
- **Walk away (run away) unreclaimed**

  Historically, walking away from the site unreclaimed was the only closure goal.
- **Zero liability**

  Some mines are cognizant of ongoing long-term liability (but many do not seem to be so).

Cultural

- **Aesthetics**

  While most miners will go to great lengths to deny it, most reclamation is done to improve the aesthetic qualities of the land, mostly visual but also for other the other senses. In some cases, the goal is to produce a landscape that is visually appealing.
- **Avoid disturbing archaeological sites**

  In some cases, borrowing material for reclamation capping is limited by the presence of archaeological sites at the borrow area. In most cases, these sites can be disturbed after a thorough archaeological investigation is completed, but in some cases, the land is set aside.
- **Avoid hard erosion control measures**

  Several sites have indicated the desire not to have concrete works or heavily armoured streams as erosion control measures, presumably because the resulting streams do not have a natural appearance.
- **Avoid sabotage**

  Some mines, especially in war-torn, aim to have reclamation that presents little opportunity for damage by sabotage (for example, tailings ponds near urban centres). More recently, risk from eco-terrorists is creeping into risk assessments.
- **Avoid vandalism**

  The goal of many sites it to avoid vandalism, particularly vandalism that results in increased costs and decreased public safety. To this extent, efforts to hide remediated sites from the general public are often undertaken. This is particularly true for mine portholes near larger cities.

- **Build goodwill among stakeholders and regulators**
  In many cases, reclamation is done with the aim of demonstrating a good track record with local and other stakeholders. This may be one of the more important motivating factors as it reduces hostility and makes expanding or opening new mines (even in new areas) much easier.
- **Don't restrict livestock wildlife with fences**
  Restriction of livestock and wildlife with fences is frowned upon in some areas. Fences are often cut or stolen. Some groups, especially the Navajo, do not seem to recognize fenced land, the land is held communally. Thus the goal of some reclamation is to avoid the need for permanent (and often temporary) fencing.
- **Employment/jobs/construction company/spending others money**
  Especially in abandoned mine areas, there is a focus on reclamation as a mechanism to infuse money and capital into a local economy.
- **Historical preservation**
  To some people, the signs of mining (old buildings, old waste piles) is a pleasant reminder of days past. Some mine wastes are protected from reclamation for these reasons. In some cases, the buildings need to be culturally documented before being removed. In some cases, historic conditions are re-created.
- **Involve the community in research and reclamation**
  Some aspects of reclamation are specifically designed to involve the community members in research and reclamation activities. This allows people to feel part of the reclamation, take pride in the whole work, and makes much of the efforts more transparent and real to stakeholders. Often, employees are targeted as part of the community.
- **Limit vehicular and other unauthorised access (trespassing)**
  Many mines use gates or berms and other physical measures to limit access, some use security measures. The concern is for the physical safety of trespassers and the effect on then landscape. Locked gates and signage are thought to reduce the company liability. Sometimes only areas that will require ongoing maintenance will have restricted access. Widespread one-person mining of old deposits is a fact of life in some developing countries.
- **Remove scrap and trash**
  One of the major steps in mine reclamation is the removal of scrap and trash including old machinery, tires, lunch debris, posts and weirs, signs, pipe, wire, etc.
- **Retribution**
  The goal for some groups in the reclamation of a site (especially land owners) is to seek retribution from the mining company for any variety of reasons.
- **Road reclamation**
  Haul roads and light vehicle roads may or may not be reclaimed based on whether the mining company wants to provide easy access to the site for future users. Generally some roads on a site are reclaimed, but major ones are not. There is some concern when the haul roads contain radioactive materials.

- **Satisfy local residents**

  Some aspects of reclamation may be done or avoided to satisfy local residences. For instance, blasting of highwalls for reclamation may be avoided. Similarly noise and trucks and redisturbance may not be wanted.
- **Visual similarity**

  To provide a landscape which will eventually look like adjacent areas is often a goal. In some cases, success is measured if a person cannot tell the difference between the reclaimed areas and surrounding undisturbed area.

Regulatory

- **Avoid declination or certificate**

  Mines often hold onto land to avoid being turned down for bond release or reclamation certification.
- **Avoid non-natural materials**

  Avoiding non-soil/vegetative materials that will decline with time. Examples include avoiding fences, Gabion rock structures, concrete, dams, etc.
- **Cover mine waste**

  Most mines create wastes that are either somewhat toxic or not that amenable for good vegetative growth. Most mines are required to cover or otherwise contain these waste materials.
- **Don't be too complicated**

  The goal of some reclamation is to be straightforward and not too complicated. In at least one case, complicated designs (such as meandering streams) have been turned down as being too complicated by regulators.
- **Meet soil capability guidelines**

  In Alberta, soil capability (rather than measured productivity) is used.
- **Meet vegetation requirements, especially percent cover**

  This is a major concern in arid areas to meet percent cover requirements that are often based on pre-mining levels or reference area levels. At one site, a percentage of the original cover percentage is applied as a minimum (but does not seem to have a scientific basis).
- **Meet water quality (on site and off site)**

  Most regulations provide limits to total dissolved solids in water on the site and off the site. In some cases where the water is already clean, drinking water standards are used for environmental water.
- **No subsidence**

  Excessive mine subsidence is a major concern, even in sloped backfills of open-pit areas. It may be a way to ensure some form of compaction of the soils for non-subsidence reasons.
- **Pork-barrelling**

  In some cases, mine reclamation is designed to create employment and transfer funds to specific regions. This is more common with state-sponsored reclamation.

- **Regulatory approval/compliance**

  Regulatory approval (en route to getting bond release) is a major driver in the reclamation process. However, mine operators do not want to spend too much time/effort with regulators and lawyers. Many mines focus on getting reclamation certification.

- **Solids loading and offsite erosion /deposition criteria**

  The site should not be producing solids deposition or downstream erosion.

- **To remove any contaminants from the site**

  Most sites are concerned with off-site transport of contaminants, a few interested in removing the contaminants from the site. Usually in any area contaminated by reagents or spilled diesel fuel are cleaned up, the remaining low-mineralization of the rock cannot be removed.

- **Uniform slopes with no gullies, potholes or depressions**

  Some land-contouring legislation does not allow for deviations from uniform grading.

- **While in its dormant site, have it meet environmental regulations**

  Mines in a dormant state need to meet environmental regulations as would an active mine. Sometimes some of the reclamation activities (such as topsoiling and revegetation) are used to reduce erosion to meet these interim goals.

Physical

- **Avoid aeolian erosion**

  Many natural sites are marginally stabilized by vegetation and changes in the vegetation results in wind erosion of the soils. Mine reclamation often seeks to avoid this type of erosion, especially from tailings areas, and most especially where the erodible sediments contain toxic metals.

- **Avoid animal erosion**

  Some sites are fenced to avoid animal erosion of soils. This is most often a concern where unwanted grazing of livestock may occur.

- **Avoid off-site seepage contamination**

  Contain seepage water on the site, often using the space in the mined-out pit

- **Avoid river erosion**

  To armour newly constructed or otherwise affected stream to have no erosion under some prescribed flood event. In some cases, to have all areas of the watershed to be stable under a prescribed climatic precipitation event.

- **Avoid seismic damage**

  Mines in seismic areas usually need to provide stability even under large earthquakes, for dumps and especially tailings areas.

- **Avoid spontaneous combustion of (coal) spoils**

  Some sites have coal spoils that are subject to spontaneous combustion (the coal oxidized and heats enough to cause the coal to ignite creating heat, air pollution and ash). The goal of closure in these areas is to avoid this problem usually by either preventing air or oxygen from reaching the coal.

- **Cleanup and removal of infrastructure**

  In most areas, infrastructure is removed including buildings, signs, fences, equipment, etc. However at many sites, foundations are left behind, perhaps as being low priority for risk to human health.
- **Cover bad materials**

  Covering radioactive or chemically unsuitable spoils is an objective common to most projects. In some cases, the cover thickness is chosen on the basis of attempting to keep roots of plants from tapping into toxic layers thus bringing the toxicity to the surface.
- **Geotechnical stability**

  Have a landscape relatively free from slumping or other kinds of landslides. In some cases also refers to absence of turbidity flows or large subsidence.
- **Have little erosion and no off-site erosion.**

  Most sites aim for little or no erosion and minimal erosion (carried by water) to offsite areas.
- **Low risk to human health**

  The sties should provide low risk to human health including chemical, biological, and physical hazards.
- **Maintain water cap**

  Isolate tailings, waste rock, or other waste from the environment by use of a water cap (forming a lake). Often, this technique is used to isolate ARD from oxygen.
- **Removal of physical hazards**

  Removal of highwalls, open shafts, portals, vertical shafts, decrepit buildings, blasting supplies etc is one of the highest priorities.
- **Restore aquifers**

  In some areas, aquifers (particularly coal aquifers) are removed during mining. In some cases, there is an attempt to restore these aquifers.
- **Use micro- and meso-topography to control erosion and add diversity**

  Creation of micro-topography (mounding or roughness at the metre scale) to create varied soil moisture conditions and local diversity. Others use meso-topography (10 to 100 metre scale) roughness to divide watersheds, limit erosion, and create diversity of aspect and moisture.

Land-use

- **Chose land uses that are the cheapest to create**

  Some mines attempt to chose land uses based on cost. Sometimes, wildlife habitat is seen as a cheap alternative.
- **Commercial forestry**

  This includes planting of reclaimed land to commercial forest restocking guidelines.
- **Create a hydroelectric facility**

  Some mines use the head created by a tailings dam to create hydropower, or to sell existing hydro facilities to local municipality.

- **Create a mix of land uses**
  One goal is to create a suitable mix of various land uses, perhaps in proportion to predisturbance areas.
- **Create aquaculture**
  Some mined out pits can be used for raising fish (aquaculture) as can some cleaned out vessels such as thickeners.
- **Create farmland**
  Farmland can be created to be suitable for agricultural crops.
- **Create fish habitat**
  This is the provision of fish habitat through stream restoration, enhancement, recreation, or creating fish habitat in mined-out pits as end-pit lakes. Species mentioned often include rainbow trout, northern pike, walleye, perch and minnows. Sport fishing is usually associated with these goals. Sometimes, lakeshores are roughened to increase fish habitat.
- **Create gardens or spas**
  More than a few mines have been converted into tourist gardens or health spas.
- **Create grasslands**
  Some mines create grassland areas suitable for wildlife, grazing, or grassland ecosystems.
- **Create industrial park**
  Many mine areas are suitable for use as industrial park, having large flat areas, road access, power, water, electricity, often natural gas, and a highly trained workforce and are suitable for light or heavy industry. Sometimes, smelters or mills will continue to operate long after the mine or mines are shut down.
- **Create landfills**
  Mine pits can sometimes be used as landfills for urban garbage. They typically have huge capacity and good access.
- **Create natural area**
  Some mines create an area that is biologically diverse, often with native plants (either planted or invading), usually in support of recreational and wildlife goals.
- **Create park**
  Areas of some mines are turned into park areas, with trails and other services.
- **Create ranchland**
  Some mines create ranchland suitable for grazing. Sometimes water holes for livestock are built in.
- **Create wildlife habitat**
  Mines can provide ecosystems, and in particular vegetation and occasionally topography, that support wildlife habitat. Often, specific species are identified – for example geese, deer, bears, cougar, beaver, eagles, marmots, deer, moose, migrating birds, elk, muskrat, mink, ermine, marten, otter, beaver, rabbits, squirrels, wolf, coyote, lynx, wolverine, birds, mountain sheep. Hunting is usually associated with this activity.

- **Return land to original land use**
  It is common to attempt to return mine land back to its original use, often to natural area or farmland.
- **Recreation**
  Recreation includes extensive (widespread low density activity like hiking or hunting) or intensive (localized high density such as a public beach, golf course, etc). May include creating areas suitable for 4x4s or dirt bikes, quads, snowmobiles. May include wildlife resource such as hunting, guide/outfitting, trapping, outdoor recreation, birdwatching, animal watching.
- **Return of original land use**
  This is a very common closure goal and may include grazing, wildlife, trees, parkland, agriculture, subdivision, or whatever the owner wants).
- **Traditional land use**
  Create landscape that are suitable for traditional land use, typically by First Nations peoples. Typical goals include creation of areas good for trapping, berry picking, medicinal plants, hunting.

Biological

- **Creation of wetlands**
  Creation of wetlands is a common goal for increased waterfowl productivity, to replace disturbed wetlands, or as a bioremediation device. Sometimes, twice the amount of wetlands can be created offsite in return for taking wetlands from the site. That said, wetlands are often instrumental in trapping sediments, mitigating metal release, and attenuating peak flows.
- **Edge effects for wildlife**
  The border between natural and reclaimed areas is often left rough to promote wildlife habitat.
- **Equivalent land capability**
  Restore land to the equivalent pre-disturbance soil capability for forestry or agriculture.
- **Good as or better than mining or better than before revegetation**
  Some projects seek to make the land as good or better than before in terms of productivity and stability.
- **Green up historic mining areas**
  As a show of good faith, this involves greening up the grandfathered historical mining areas.
- **Green up the site**
  Most mines are attempting to revegetate the site, mainly in an effort to green it up. This is usually accomplished using agronomic grasses, sometimes with shrubs or trees. Some sites work especially to green up areas that are visible from roads or lakes.
- **Kick-start the natural successional process**
  Planting strategy to stabilize the land cover and be amenable to natural invasion. Often just lip-service, some shade and avoiding monoculture strategies are employed by others.

- **Meet a bioproductivity level**

  Getting bioproductivity levels back to pre-mining disturbance seems to come from agricultural standards. Part of the percent cover may come from this idea. Meet vegetation productivity requirements. May be spelled out at achieving productivity on the reclaimed mine land equal to that which existed prior to mining, on an average property basis
- **Meet soil chemistry requirements**

  Some groups seek to meet specific soil chemistry requirements.
- **Mimic reference area**

  Often it is attempted to have the system perform biologically like a chosen reference areas.
- **Not to favour coyotes**

  Some of these rock sites favour coyotes which are not desirable to many people.
- **Planting diversity**

  Having diverse species, and particularly avoiding monoculture plant communities is an oft-stated objective. This more closely mimics nature and has more robustness from droughts and pests. To many, this is just to avoid planting monoculture. Sometimes seeding of dozens of species is used, but this often results in a monoculture.
- **Promote rare wildlife (bats) or exotic wildlife**

  Some areas attempt to promote high-profile wildlife. In particular, many abandoned portals contain bats, so sealing up of the portals is sometimes not desirable and so bars that keep humans out but allow bats in (bat gates) are employed.
- **Provide diversity of slopes and vegetation**

  Some feel it is important to provide a diverse set of soil, slope and vegetative conditions on the site.
- **Restore damaged offsite lakes**

  Restore the ecology (and especially fish populations) in offsite lakes damaged through mining or smelting activities.
- **Restore native vegetation (non-exotic)**

  Many groups seek (or are driven) to plant species that were present in the pre-mining area.
- **Rocks for rodents**

  Some areas attempt to promote rodents by piling rocks to create rodent habitat.
- **Soil conservation**

  Soil conservation is a key area, especially in agricultural areas or arid areas with little soil resource. Conservation of any topsoil become an integral part of a reclamation plan.
- **Sustainability**

  Most site plan (hope) for self-sustaining (no replanting, watering, fertilizing) ecosystems.
- **Water for cows**

  Some reclamation plans attempt to create water ponds for cows to drink from.

Chemical

- **Store water**
  To collect 90 percent of contaminated surface and ground water and pump to main pit to hold 60 years to begin water treatment.
- **Water discharge without treatment**
  This goal enables mines to discharge mine-pit lake water to the environment without treatment, or to create passive ARD remediation conditions (such as a wetland system).

Other

- **Able to drive a truck over it**
  Some mines aim for being able to traverse the entire site by truck (especially agricultural area).
- **Create test areas**
  Some areas are set aside just to create test or research areas for testing of new or existing techniques.
- **Just be stable**
  Some areas are just intended to be stable and nothing else. Sometimes this is referred to as just being "an okay part of the watershed."
- **Manage water infiltration and runoff**
  Landscapes are sometimes designed to retain water (usually through wetlands or enhanced infiltration) or to shed water (as in covers for acid-producing dumps or tailings).
- **Meet personal needs**
  A lot of mine reclamation activities are designed to meet unstated personal goals of the environmental people.
- **Meet professional requirements**
  Some professionals recognize their over-riding duty to society and this may impact on their goal setting.
- **Mimic natural conditions**
  Mimic (perhaps without complete understanding) the natural topography, natural streams, or natural vegetative communities.
- **Return spirituality to land**
  Repairing the damage done by mining and restoring natural ecosystem (and through ceremonies through the process) restore the spirituality to the land. Sometimes this includes a desire to avoid letting the devil (or a monster) out of the mine pit or shaft.
- **Stop human habitation**
  In some areas, there is an attempt to avoid human habitation of affected areas, especially areas that have radioactive waste rock or tailings.

- **To create long-term employment**
  The goal of some is to create areas that will provide long-term employment, either through long-term maintenance or in new land uses.

Supplement B

Compendium of challenges to mine reclamation

This supplement captures many of the challenges to mine reclamation based on visits to 69 mines. Table 3.1 and Figure 3.4 provide summaries of this supplement.

Design and planning

- **Abandoned mines**
  Abandoned mines come with their own set of problems including lack of funding, lack of owner, lack of records and unknown locations.
- **Closure planning separate from daily operation**
  Here, closure planning activities are not linked with reclamation activities – the two are done in isolation.
- **Competing goals/objectives**
  Many of the objectives are in direct competition when it comes to final land use.
- **Complete lack of design**
  Many mines have a complete lack of reclamation design beyond greening up the landscape.
- **Complexity**
  The workings of a reclaimed site, considering all the interactions and uncertainty, is a highly complex system. The complexity itself makes this work a real challenge.
- **Doing what you do well, ignoring the rest**
  Many mines tend to concentrate on what they can do and what they can do well and seem to ignore other important factors.
- **Eternal optimism vs geologic and ecological reality**
  Mines are eternally optimistic about the performance of their reclamation, downplay potential hazards, and sometimes overlook geologic and ecological reality. Senior management is particularly prone at overselling future performance.
- **Existing structures**
  Existing structures, designed and constructed in earlier days create a desire to work with them rather than retrofitting and need special consideration. This is especially true for tailings and other dams, but also for pits, roads and waste rock dumps.
- **Future owner abuses site**
  Future owners of the site, particularly companies that mine or re-mine the site, can cause damages that previous owners of the mine may be responsible for.
- **Imperfect understanding of nature**
  No mines have a full understanding of natural systems but mines are not generally looking at natural systems to mimic.

- **Keeping track of commitments**
  Mines make a lot of environmental commitments, especially in dealing with stakeholders and more especially during permitting and hearings, that result in difficulties just keeping track of all the commitments.
- **Lack of a system**
  Almost no mines have an integrated system for reclamation. It is generally just greening up the site.
- **Lack of data**
  Most places do not collect data on reclamation and in many cases, rainfall and hydrological data is sketchy and the lack of data hinders the design process.
- **Lack of precedence**
  Often reclamation is done using methods or with materials or scales that lack precedence.
- **Lack of reliability, predictability**
  A lack of predictability and reliability of long-term landscape performance is a challenge.
- **Lack of staff, outside influence, isolation**
  Most mines have the barest of technical staff and many work in isolation. Sharing of ideas does not seem to occur, and often major items are missed. Lack of hydrologic design skills is a common factor.
- **Loss of records, staff turnover, poor continuity**
  Some operating mines and most abandoned mines have difficulty with records and continuity.
- **Low factor of safety**
  Engineers can win awards for building dumps and dams with low factors of safety and it is not always clear that these structures, even if they reach their final stage of construction successfully, will remain stable in the long term.
- **Low grade stockpiles**
  Mines often leave behind low-grade ore stockpiles to mine at a future date. If these never become economic (or fit the mine plan), and are left to closure, they are often a source of contamination.
- **Missing key hazard**
  Almost always missing/minimizing key aspect, no hazard assessment: The mines to not seem to use hazard assessment techniques to identify key problem areas.
- **Site never had a closure plan**
  Perhaps the main challenge is that the site was not designed or mined with closure in mind. Lack of closure plans, poor mining practice, incomplete plans (Planning is often done on the fly, and most mines do not have a closure/reclamation plan. It is unclear whether enough materials will be available for final reclamation after production has ceased.)
- **Stakeholder involvement**
  Most mines do not seem to have stakeholder involvement other that with the regulators.
- **Surface water hydrology ignored**
  In at least half of the mines, hydrology is ignored.
- **Too focussed on biology (revegetation)**

- **Coal surcharge paying for AML and AML**

  A coal surcharge is applied on coal companies and applied to other industries thus cross-subsidizing other industries at he expense of coal.
- **Dealing with dormancy from a regulatory point of view**

  Having mines pull up operations and go into dormancy provides unique challenges from a regulatory point of view, especially when the dormancy is mainly aimed at not spending money on reclamation.
- **Government owned lands, intergovernmental conflict**

  In some cases, there is intergovernmental conflict on land use and regulation.
- **How to fix things when they are unfixable**

  In some cases, there are now ways to economically fix up problems and meet all the goals. It is a challenge for regulators to prevent mines from reaching this point and even more of a challenge to figure out the best course of action.
- **Imported regulations**

  Most regulations are imported from other jurisdictions. Some are modified during import, others not. In a lot of cases, the imported regulations make little sense to the new region or to the particular minesite.
- **Ineffective regulators**

  Due to political interference and reduced numbers, regulators are often ineffective at minesites.
- **Intervention of politicians and powerhouses**

  Intervention of politicians and strong members of industry is often disruptive to reclamation and closure regulation.
- **Long time lags to certification**

  Certification usually lags behind reclamation by a decade or more. When it comes time for certification, one is measuring old reclamation methods against old goals and it is sort of like buying a used car, complete with old technology and not a few dents and scratches.
- **Not challenging regulations of beliefs**

  Many of the regulations and beliefs are held firm and not challenged, even when they make little sense.
- **Power of individual mines**

  Sometimes major mines wield too much power, threatening economic collapse in response to changing regulatory conditions.
- **Power of individual regulators**

  Individual regulators and often individual inspectors wield a lot of power, sometimes disproportionate to their mandate.
- **Too complex for regulators**

  The intricacies of mine reclamation and long-term reclamation performance may be too complex for the presently regulatory system. Individual inspectors have an unclear mandate and cannot understand all the implications and technical information from all the specialists in different fields. Regulators are often poorly skilled in integrating from different sciences.

An regulations are generally based on the idea of a static landscape, and the frameworks are sometimes unable to deal with the complexities of changing and evolving landscapes.

- **Unclear, conflicting, overlapping, and numerous regulatory goals**
  It is often impossible to satisfy all regulatory goals at the same time.
- **Unreasonable time frames**
  Mines are often asked to provide assurance of good landscape performance hundreds or thousands of years into the future.
- **Variable regulations between states and countries**
  In some cases, there are different standards and goals between different levels of government charged with overseeing reclamation. Some minesites straddle different legal jurisdictions. As well, there is often friction between government departments, particular the mines branch and the environmental protection group.
- **Visual overriding physical realities**
  In some cases, regulators are requesting reclamation to improve visual (aesthetic) components of reclaimed landscape that are either unproven or may lessen the change of reaching other goals, particularly stability goals.

Physical

- **Autocompaction**
  Compaction of soils is a problem for some mines as it inhibits good vegetative growth.
- **Changing infiltration rates**
  Infiltration and percolation rates may change with time as soil become more developed (or weathering of waste rock) or as subsidence and cracks or vegetation pattern changes change the rates of infiltration and runoff.
- **End pit lake performance**
  End pit lake performance is difficult to predict, and more so when it is asked to be part of a passive ARD remediation system or other form of bioreactor.
- **Establishing drainage on flat areas**
  Establishing good drainage on flat areas can be difficult as deep ditches are often required. This is particularly true of retrofitting drainage to previously constructed areas.
- **Extreme climate**
  Extreme climates such as high precipitation, permafrost, high altitude, torrential rains, droughts, high heat, are especially challenging for reclamation. The most difficult areas are likely those in bad-land or desert areas where it is difficult to establish vegetation and even natural vegetation is sparse.
- **Geotechnical instability leading to further poor performance**
  Geotechnical instability can lead to landslides which block drainages, cracks that disrupt surface drainage, and pitwall cracking may crack back into dumps.

- **In maintenance, no provision for extreme events, no risk assessment**
  Long-term maintenance may not have provision for extreme rainfalls or other events, and often no risk assessment to ensure that structures such as dams can resist such elements.
- **Leaving behind large tailings dam and pond**
  Leaving a large, high, steep sand tailings dam with a pond above in the final landscape. (Mines can win awards for such dams, but are a real problem when it comes to closure.)
- **Long term geotechnical stability**
  The long-term geotechnical stability of slopes may be in doubt due to low factors of safety, seismic concerns, materials losing strength with time (softening or progressive or delayed failure), rising water tables (perhaps with climate change), toe erosion by rivers or lakes, or other phenomena.
- **Mountain top end-pit lakes**
  End pit lakes from mountain top mining are difficult to fill as there is very little watershed.
- **Physical risks to people and animals**
  Mines sites often leave behind physical risks to people including landsliding, quicksand/soft ground, thin ice, spalling, sinkholes and depressions. Some of these will only develop after long periods of time.
- **Rock fall hazards**
  Dealing with rock fall hazards from final pit slopes, especially around end pit lakes is challenging.
- **Seismic risk**
  Good long-term performance of landforms is even more difficult in highly seismic zones.
- **Site hydrology poorly understood**
  Most mines have a poor understanding of site hydrology, the water balance, infiltration rates, climatic conditions, flood patterns. This makes technical design of the landscape very difficult, especially for larger sites.
- **Site underlain by pervious substrate**
  Sites that are built on predominantly sand or gravel substrates are especially challenging for limiting seepage – worse when the problem is not recognized prior to construction.
- **Subsidence**
  Subsidence can lead to disruption of drainage, enhanced infiltration, changes to soil regime, and impact on civil structures.

Chemical

- **Acid rock drainage**
  Any site that produces acid rock drainage is challenging to reclaim.
- **Close proximity of mine wastes to environmentally sensitive area**
  Some mine waste areas are immediately adjacent to sensitive areas such as rivers, streams, and wetlands. The geographic proximity makes remedial measures difficult and more time sensitive.

- **Disposing sludge water treatment**
  Many mines find that it takes only a few decades to fill the mined out pits with sludge from ARD water treatment. The large volumes make the sludge difficult to manage, especially in the long term.
- **Groundwater ignored**
  Minesites with groundwater problems are challenging. Many mines ignore groundwater entirely and don't even know if there is a problem.
- **Large amounts of ARD producing material**
  Many sites have huge inventories of acid producing materials that will take millennia to flush out and essentially perpetual water treatment.
- **Long term leaching**
  Slow long-term leaching of low-reactive acid producing materials may prove problematic in the future.
- **Mitigation of deep-lake or ocean disposal**
  Chemical mitigation of deep lake or ocean disposal of rock or tailings would provide difficult.
- **Problem soils**
  A lot of sites have to deal with problem soils, whether they are dispersive, sodic, saline, have high metals, or any number of problems that make growing lush ecosystems challenging.
- **Radioactivity**
  Radioactivity at a site makes reclamation difficult, and a PR nightmare.

Land use

- **Some agreed upon land uses difficult to achieve**
  Examples include forest in a desert, luxury subdivisions on undermined land, Class A provincial park.

Biological

- **A major game-fish stream flows through the site**
  Some mines operate and close with a game fish creek flowing right through the middle of the site. In another case, a mine is surrounded by a lake where fishing is very important.
- **Animal effects on erosion**
  Some tailings sand slopes are unlikely to be able to be able to withstand wildlife grazing.
- **Animal effects on vegetation**
  There are often problems in newly reclaimed areas with animals browsing on bushes and trees or mice gnawing on the bark. This can make establishment of shrubs and trees very difficult in some areas. Burrowing animals can also cause problems.

- **Beavers**

  Beavers present a formidable challenge to reclamation. Their dams threaten to overtop levees and dams, divert streams, flood large areas, change riparian habitat, and consume vast quantities of young trees.
- **Climatic variability**

  Some years are very wet or very dry and seeds or seedlings planted over large areas may be washed away or bake dry. Particularly a problem in desert areas where it rains infrequently and the heat reduces seed viability.
- **Hard to re-establish vegetation**

  Re-establishing any vegetation in desert reclamation can be very difficult.
- **Lack of organic soil**

  Many mines have a near lack of organic top soil and end up having to seed the capping dirt. This is particularly true in desert and mountain mines.
- **Redisturbance**

  Redisturbing reclaimed area either to re-reclaim it or to provide access for gully or other fix-up is often a challenge and sometimes avoided.
- **Use of native species**

  Some areas restricted the use of non-native species, but revegetating drastically disturbed using exclusively native seed can be challenging in many ways.

Other

- **Education in remote areas**

  It's challenging for reclamation specialists to keep current in their training and share information with others working at isolated mines in far off communities.
- **Hazardous conditions to reclamation workers**

  In some cases, especially working with radioactive mine wastes, there is considerable hazard to reclamation workers, which presents its own challenges.

Supplement C

Compendium of novel concepts

This supplement captures many of the novel concepts seen or heard at visits to 69 mines. Table 3.1 provides a summary of this supplement.

Design and planning

- **Adaptive science**
  One cannot forecast all outcomes from the start – research programs cannot be laid out in detail over several years, they need to be adaptive.
- **Aim for no ongoing liability**
  Aim for no ongoing liability after closure, and aim to clean up and walk away from sites except where it is not practical or economical to do so. Then aim for low levels of passive maintenance on a declining basis.
- **Annual environmental audit**
  Members of a company get together at one or two of the company's mine each year to review the environmental performance and the existence of systems. The audits are done professionally, and something of a code has developed – things are not overlooked, but everyone recognizes that the same team will be visiting their mine in the near future. The audit is a chance to share information, achieve and audit, and help keep everyone on his or her toes.
- **Avoiding problem habitats**
  It is cheaper to avoid habitats than to put them back (for example, wetlands or river valley slopes at the edges of mining areas).
- **BADCT Best available demonstrated control technology**
  Some mines are considering borrowing from the water treatment strategies for choosing and defending technology used for mine reclamation. This approach is not performance based, but is rather technologically based and is only occasionally useful for mine reclamation. Other acronyms along the same line include: BATNEEC (best available technology not entailing excessive cost), BPEO (best practicable environmental option), BACM (best available control measures), BACT (best available control technology), BADCT (best available demonstrated control technology), BADT (best available demonstrated technology), BAT (best available treatment), BATEA (best available treatment economically achievable), BDAT (best demonstrated achievable technology), BDAT (best demonstrated available technology), BDT (best demonstrated technology), BEJ (best engineering judgement), BEJ (best expert judgement), BMPs (best management practices), BPT (best practicable treatment), BPJ (best professional judgement), CATNIP (cheapest available technology not involving prosecution).
- **Burying of worst waste at depth**
  When backfilling pits, the most toxic materials are placed first (lowest) and capped with progressively more benign material.

- **Closure planning to establish research priorities**
  Closure planning is a useful too to establish research priorities and their timing.
- **Decision analysis**
  Using the techniques of decision analysis for choosing between alternatives for reclamation technologies.
- **Diversity**
  Some mines aim for diversity in soils, aspect and vegetation.
- **Early monitoring**
  If a prospect seems likely to become a mine someday, establishment of a climate station, and monitoring of streams (for flows and water quality) at an early stage can pay great dividends for closure planning for the mine. It also helps to start research on any showstoppers (like endangered wildlife) as soon as possible in anticipation of permitting problems.
- **Ecological engineering**
  The old/new field of ecological engineering provides a good design basis or framework for achieving viable ecosystems on reclaimed land.
- **Establish a corporate commitment**
  Critical to the success of reclamation and closure is a corporate commitment at the highest level to do a good job.
- **Focus on minimizing liability**
  Few practitioners realize that they are hired to perform planning and reclamation activities to reduce corporate liability.
- **Honest effort is what counts**
  While not everything needs to be perfect, due diligence and an honest effort needs to be demonstrated.
- **Landscape architecture**
  People are applying landscape architecture techniques to mine reclamation, particularly for specific areas of the sites, with a focus on visual aspects and continuity of landforms.
- **Naming conventions**
  Uses of the words waste dumps and tailings pond is familiar to all miners, but may mislead the public (who often think the dumps contain rubbish and the tailings areas are nice ponds). Mines have started to refer to these as rock disposal sites (RDS) or overburden storage areas (OSA) and tailings storage facilities (TSF)
- **Planning horizon limited to 50 years**
  It's difficult to plan in any detail for more than 50 years hence.
- **Recognition of exploration damage**
  Often exploration can cause considerable environmental damage and sites of intense exploration should have their own closure plan, especially given that most exploration areas do not become mines.
- **Recognition that every site is unique**
  Regulations are often crafted to cover all sites, but every site is unique and deserves special design and treatment.

- **Risk assessment**

  Using Failure Modes and Effects Analysis (FMEA) can effectively address risks and mitigative measures for reclamation and landscape performance.
- **Risk-based criteria**

  Choosing design criteria based on risk is effective – small streams could be designed with withstand say a one in 200-year flood if consequences of failure are small, but a spillway may be designed to handle a probable maximum flood.
- **Self-design reclamation**

  In many cases, a site can be left to self-design (with some help). For example, gullies can be allowed to form where they will (then armoured), and volunteer plants can be allowed to come in.
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  Each site has a technical team that runs the mine and also takes care of closure issues. The team includes mining and mechanical engineers, a team of planners, an environmental person, an owner's representative and many consultants. The environmental department pays for the costs of putting together a closure plan and also for the mine reclamation. Others on staff at this site in the environmental department include two engineers and two biologists.

  Most reclamation is done by simply follow a few key prescriptions, but in some instances, careful design is performed.
- **Trial and error reclamation**

  A common approach to reclamation is trial and error, trying different things on a plot of land until something works. Hydroseeding numerous time until the plants catch is a good example. Not often the best strategy, but widely used, and likely useful in some circumstances.
- **Use of design principles**

  Most reclamation is done by simply follow a few key prescriptions, but in some instances, careful design is performed.

Reclamation construction

- **Acid mine drainage control through planning**

  Likely the greatest single impact on cost and environmental performance for acid rock drainage is its identification before construction work starts on the site, and segregation of the reactive materials through proactive mine planning.
- **Active maintenance of checkdams**

  Use of rock or soil checkdams and providing active maintenance that would be passed on to the landowner after closure.
- **External review and audit**

  Reclamation activities and landscape performance subject to audit and external review as a method of ensuring good reclamation.

- **Field fitting reclamation and terraces**
  Much of the reclamation work need not be figured out in final detail in the office, certain elements, particularly microtopography and drainage, are better field fit by qualified people in the field.
- **Going offsite for capping materials**
  For mines where there is not enough capping material to cap the wastes, mines debate whether to enlarge their disturbance by going offsite.
- **Paste backfill**
  Tailings is used for hydraulic fill for underground workings. Using cement-paste technology, this reduces the amount of tailings (and acid producing materials) at the surface, stabilizes the underground workings and usually saves the company money.
- **Removal of entire waste dumps and tailings ponds**
  Some sites require complete backfilling of old open-pits to original contours. This may mean re-mining the tailing and waste rock dumps after closure.
- **Removal of entire waste dumps and tailings ponds for placement in mined-out pit**
  In some cases, entire dumps and tailings ponds are moved again for placement in mined-out pit.
- **Removing trash**
  Most mines create a tremendous amount of trash, even in reclaimed areas. Items include scrap metal, old fence, tires, food packaging wastes, and old culverts. Keeping the site free from this trash at all times during the operation is cheaper and more effective than going back to remove it under contract at a later date.
- **Rounding of pit crests**
  Some pit crests are rounded to provide warning to wildlife of the nearby pitwall cliff.
- **Specialized reclamation equipment**
  Most reclamation is done with loaders, trucks and dozers, and often farm equipment, but some mines are using specialized equipment such as manure spreaders, and others are considering specialized equipment such as spreaders, hydraulic placement of reclamation material, specialized tractors.
- **Stockpiling reclamation soils on haul roads for eventual closure of the roads**
  Haul roads often need to be active for reclamation activity. One mine is placing a double thickness of half of the wide haul road, so that for final reclamation, a dozer can be used to spread this material over the other half of the haul road for final reclamation at a later date.
- **Use of a well-known, well-respected contractor consultant for all biological reclamation work**
  Use of a well-known contractor for reclamation can help to ensure acceptance and good work.

Monitoring and maintenance

- **Annual reports**
  Summariziation of annual monitoring and all research programs into an annual report, including oblique aerial photographs and annual photographs from surface photo-stations.

- **Good use of signage**
  Signage at the reclamation sites explains reclamation for employees and people on tours.
- **Long-term monitoring plans**
  One site has a twenty-year monitoring program planned.
- **Modem communications and alarms to permit offsite monitoring and control of pumps**
  Pumps and infrastructure at long-term maintenance sites can be controlled from offsite.
- **Photo spots and tour spots**
  Some mines have great spots for taking pictures for showing changes over time. Others also have good spots for tour stops to show the reclamation. It may be worthwhile to create these in the mine plan rather than as an afterthought.
- **Standardization of equipment**
  Standardization of all pumps, pipes, wire, and monitoring for pumping to increase reliability and reduce inventories of parts
- **Slump and gully fix-ups are being done as required**
  As slumps and gullies form, they are being repaired as part of long-term maintenance.
- **Use of GIS**
  A geographical information system (GIS) is being used regionally and for each site. A wide range of environmental data, including electromagnetic surveys is going into the GIS which is resulting in it becoming an integral monitoring package and a vehicle for closure planning, reclamation and monitoring.
- **Use of remote sensing**
  Remote sensing is being used for site wide monitoring, particularly the use of annual aerial photographs and new high-resolution satellite imagery.
- **Yearly site monitoring and maintenance.**
  Some sites perform yearly monitoring of the entire site and use this monitoring to plan maintenance programs.

Financial

- **Blurred division between mining and reclamation**
  If mining and reclamation are well integrated, it is hard to determine what costs should be proportioned to mining and which to reclamation (where does mining end and reclamation start?)
- **Buying liability with minesite**
  A mining company purchased a dormant site for reserves but decided not to mine, responsible for reclamation and closure just the same. Presently doing some reclamation and hoping to sell site and liability.
- **Estimating closure costs**
  Closure costs can be estimated to within an order of magnitude as a next step using a rough approach. Several options will arise on a continuum between do-nothing and entombment.

Need to avoid the idea that closure costs can be estimated to within 10 percent. In reality, it is a living number and only a ballpark estimate.

- **Historical legacies**
  Some closure activities on old mining areas on their lease is as great a task as the original mining.
- **Land value not equal to reclamation cost**
  The land value is virtually always orders of magnitude less than reclamation costs.
- **Liability needs to be continually updated for shareholders.**
  Liability changes on a yearly basis and so needs to be updated yearly for the mines annual accounting/reporting.
- **Liability of commodity purchaser**
  The purchasers of mine commodities (like a smelter purchasing ore) may be responsible for the minesites should the mines fail.
- **Logging of the site to support reclamation costs.**
  One mine that owns the land uses logging on the land to pay for ongoing reclamation costs.
- **Purchasing the outstanding shares**
  Large mining companies will sometimes purchase outstanding shares in a dormant mine to become solely in charge of reclamation activities.
- **Recognition of benefits of progressive reclamation**
  Progressive reclamation is used to reduce liability and to allow refinement of the cost estimates, support of research and development, and allow learning over time.
- **Steady budgets**
  Annual reclamation budget held constant can ensure a sustained and level effort of reclamation.
- **Time of the essence**
  In some cases, especially where short term damage to human health is a concern, there is a need to act quickly to do reclamation and stabilize the land.
- **Transparency in reclamation and decision making**
  Having a very open and transparent methodology in reclamation and decision-making can go a long way to gaining trust from regulators and stakeholders.

Cultural

- **Beautify highly visible areas**
  Highly visible areas can be beatified to increase acceptance of mining.
- **Build and donate an interpretive nature centre in a reclaimed area**
  Creation of an interpretive nature centre is a good way to promote reclamation activities, especially to school children.
- **Clean up messy areas**
  It is often worthwhile to maintain a neat site, cleaning up any areas not in active use.

- **Creation of golf courses**
  Creation of golf courses on reclaimed land is a method often used to promote reclamation and the new usefulness of the land.
- **Donation of area for clubhouse**
  Donation of a reclaimed area for a fish and game clubhouse is a powerful demonstration.
- **Fishing derby**
  An annual fishing derby in trout-stocked end pit lakes is a major hit.
- **Formation of local stakeholder groups**
  Companies creating regional technical advisory committees composed of local stakeholders to guide reclamation activities, especially related to end land use.
- **Getting local service groups or stakeholders to do reclamation**
  Contracting local service groups (such as Scouts or Guides) or stakeholder companies (such as First Nations companies) to do reclamation activities, especially revegetation, can be a powerful strategy for all.
- **Grazing problems**
  Grazing of newly vegetated areas by livestock and wildlife is a major impediment to good reclamation.
- **Historical tailings**
  Some areas, the spoils and tailings are deemed historical and protected from disturbance including reclamation. In other areas, it has been decided that there is historical value for people looking up from the highways at spoils and so the spoils are left.
- **Involving the president in reclamation**
  Involving the company president in reclamation activities is one way to achieve buy in and support.
- **Native employment**
  Native employment in reclamation is a major issue in some regions.
- **Natural looking reclamation**
  Almost everyone is trying to make their land somewhat natural looking, and having natural looking reclaimed areas is a major performance indicator for most stakeholders.
- **Religious blessing of land**
  Some native groups conduct routine ceremonies to maintain the spirituality of the land.
- **Stakeholders may not like reclamation construction activities**
  In some cases, stakeholders would prefer that the area not be reclaimed or be reclaimed in a non-obtrusive manner.
- **Uranium tailings in plaster**
  Some uranium tailings have been used in house construction and some houses are built on uranium tailings. These have to be abandoned and disassembled.
- **Use of boardwalks**
  Boardwalks, especially elevated ones, through demonstration sites like wetlands, is a powerful technique in providing access to sites.

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  Most reclamation is done with loaders, trucks and dozers, and often farm equipment, but some mines are using specialized equipment such as manure spreaders, and others are considering specialized equipment such as spreaders, hydraulic placement of reclamation material, specialized tractors.
- **Stockpiling reclamation soils on haul roads for eventual closure of the roads**
  Haul roads often need to be active for reclamation activity. One mine is placing a double thickness of half of the wide haul road, so that for final reclamation, a dozer can be used to spread this material over the other half of the haul road for final reclamation at a later date.
- **Use of a well-known, well-respected contractor consultant for all biological reclamation work**
  Use of a well-known contractor for reclamation can help to ensure acceptance and good work.

Monitoring and maintenance

- **Annual reports**
  Summariziation of annual monitoring and all research programs into an annual report, including oblique aerial photographs and annual photographs from surface photo-stations.

- **Good use of signage**
  Signage at the reclamation sites explains reclamation for employees and people on tours.
- **Long-term monitoring plans**
  One site has a twenty-year monitoring program planned.
- **Modem communications and alarms to permit offsite monitoring and control of pumps**
  Pumps and infrastructure at long-term maintenance sites can be controlled from offsite.
- **Photo spots and tour spots**
  Some mines have great spots for taking pictures for showing changes over time. Others also have good spots for tour stops to show the reclamation. It may be worthwhile to create these in the mine plan rather than as an afterthought.
- **Standardization of equipment**
  Standardization of all pumps, pipes, wire, and monitoring for pumping to increase reliability and reduce inventories of parts
- **Slump and gully fix-ups are being done as required**
  As slumps and gullies form, they are being repaired as part of long-term maintenance.
- **Use of GIS**
  A geographical information system (GIS) is being used regionally and for each site. A wide range of environmental data, including electromagnetic surveys is going into the GIS which is resulting in it becoming an integral monitoring package and a vehicle for closure planning, reclamation and monitoring.
- **Use of remote sensing**
  Remote sensing is being used for site wide monitoring, particularly the use of annual aerial photographs and new high-resolution satellite imagery.
- **Yearly site monitoring and maintenance.**
  Some sites perform yearly monitoring of the entire site and use this monitoring to plan maintenance programs.

Financial

- **Blurred division between mining and reclamation**
  If mining and reclamation are well integrated, it is hard to determine what costs should be proportioned to mining and which to reclamation (where does mining end and reclamation start?)
- **Buying liability with minesite**
  A mining company purchased a dormant site for reserves but decided not to mine, responsible for reclamation and closure just the same. Presently doing some reclamation and hoping to sell site and liability.
- **Estimating closure costs**
  Closure costs can be estimated to within an order of magnitude as a next step using a rough approach. Several options will arise on a continuum between do-nothing and entombment.

Need to avoid the idea that closure costs can be estimated to within 10 percent. In reality, it is a living number and only a ballpark estimate.

- **Historical legacies**
  Some closure activities on old mining areas on their lease is as great a task as the original mining.
- **Land value not equal to reclamation cost**
  The land value is virtually always orders of magnitude less than reclamation costs.
- **Liability needs to be continually updated for shareholders.**
  Liability changes on a yearly basis and so needs to be updated yearly for the mines annual accounting/reporting.
- **Liability of commodity purchaser**
  The purchasers of mine commodities (like a smelter purchasing ore) may be responsible for the minesites should the mines fail.
- **Logging of the site to support reclamation costs.**
  One mine that owns the land uses logging on the land to pay for ongoing reclamation costs.
- **Purchasing the outstanding shares**
  Large mining companies will sometimes purchase outstanding shares in a dormant mine to become solely in charge of reclamation activities.
- **Recognition of benefits of progressive reclamation**
  Progressive reclamation is used to reduce liability and to allow refinement of the cost estimates, support of research and development, and allow learning over time.
- **Steady budgets**
  Annual reclamation budget held constant can ensure a sustained and level effort of reclamation.
- **Time of the essence**
  In some cases, especially where short term damage to human health is a concern, there is a need to act quickly to do reclamation and stabilize the land.
- **Transparency in reclamation and decision making**
  Having a very open and transparent methodology in reclamation and decision-making can go a long way to gaining trust from regulators and stakeholders.

Cultural

- **Beautify highly visible areas**
  Highly visible areas can be beatified to increase acceptance of mining.
- **Build and donate an interpretive nature centre in a reclaimed area**
  Creation of an interpretive nature centre is a good way to promote reclamation activities, especially to school children.
- **Clean up messy areas**
  It is often worthwhile to maintain a neat site, cleaning up any areas not in active use.

- **Creation of golf courses**
  Creation of golf courses on reclaimed land is a method often used to promote reclamation and the new usefulness of the land.
- **Donation of area for clubhouse**
  Donation of a reclaimed area for a fish and game clubhouse is a powerful demonstration.
- **Fishing derby**
  An annual fishing derby in trout-stocked end pit lakes is a major hit.
- **Formation of local stakeholder groups**
  Companies creating regional technical advisory committees composed of local stakeholders to guide reclamation activities, especially related to end land use.
- **Getting local service groups or stakeholders to do reclamation**
  Contracting local service groups (such as Scouts or Guides) or stakeholder companies (such as First Nations companies) to do reclamation activities, especially revegetation, can be a powerful strategy for all.
- **Grazing problems**
  Grazing of newly vegetated areas by livestock and wildlife is a major impediment to good reclamation.
- **Historical tailings**
  Some areas, the spoils and tailings are deemed historical and protected from disturbance including reclamation. In other areas, it has been decided that there is historical value for people looking up from the highways at spoils and so the spoils are left.
- **Involving the president in reclamation**
  Involving the company president in reclamation activities is one way to achieve buy in and support.
- **Native employment**
  Native employment in reclamation is a major issue in some regions.
- **Natural looking reclamation**
  Almost everyone is trying to make their land somewhat natural looking, and having natural looking reclaimed areas is a major performance indicator for most stakeholders.
- **Religious blessing of land**
  Some native groups conduct routine ceremonies to maintain the spirituality of the land.
- **Stakeholders may not like reclamation construction activities**
  In some cases, stakeholders would prefer that the area not be reclaimed or be reclaimed in a non-obtrusive manner.
- **Uranium tailings in plaster**
  Some uranium tailings have been used in house construction and some houses are built on uranium tailings. These have to be abandoned and disassembled.
- **Use of boardwalks**
  Boardwalks, especially elevated ones, through demonstration sites like wetlands, is a powerful technique in providing access to sites.

- **Use full-scale demonstrations**

  The use of full-scale reclamation demonstrations allows testing of technologies at full scale and demonstrating the effectiveness to miners, regulators and stakeholders
- **Vandalism**

  There is a need to keep track of incidents and put controls in place to curb similar incidents in the future.
- **Visual barriers**

  Creation of vegetated visual barriers to shield some of the mine disturbance from neighbourhoods and highways.
- **Yearly planting by members of the community**

  Have a local reclamation day where members of the community are involved in tree planting. This can be co-ordinated with Earth Day activities.

Regulatory

- **Difficulty in dealing with naturally occurring ARD**

  Sites with acid rock drainage coming from mine areas often have difficulty in distinguishing background levels and are often asked to clean up to better than background levels.
- **Hard to assess sustainability when monitoring temporary measures**

  Some measures, such as temporary crops, temporary checkdams, temporary active maintenance, continued mine activities, make monitoring for closure difficult and difficult to say that one has established long-term conditions.
- **Move problem onto reservation or active site**

  Some people take their spoils away to another site. Sometimes it is to an active site where reclamation law may not apply presently.
- **Overall government agency**

  The Tennessee Valley Authority is an example of a government agency responsible for all activities in an area. For a mining region, such an authority could be created that is responsible to mines and stakeholders for proper use and reclamation of the land.
- **Poor decisions by regulators**

  Sometimes, decisions enforced by regulators produce worse environmental effects. One example, is requiring a mine to stop placing tailings in a deep lake and causing them to place tailings subaerially on a floodplain.
- **Pound of flesh**

  Most mines have about the same amount of grief with regulators and regulations – it would seem that there is a level playing field for mines, regardless of the risks faced – those with an easier job are asked to do more.

Physical

- **Allowing gullies to form, then repair/armour them to become permanent features**
  One strategy is to allow nature to indicate where the gullies are to form, then armour them into permanent features. This is a form of self-design.
- **Avoiding plateaus**
  Flat plateaus on dumps and tailings areas often perform poorly due to differential subsidence, ponding water, and shedding water onto slopes. These are usually best avoided by creating a bowl and directing water down a prepared channel.
- **Cat tracking downslope to build in rills**
  Downslope cat tracks can form rills that aid in reclamation by creating microtopography, controlling overland flow, and allowing seed to catch in the moister areas in the bottom of rills.
- **Complete hydrologic design manual**
  A drainage design manual can be created for local conditions to provide guidance in design of drainage measures.
- **Diversity in soil, vegetation and, slopes**
  It is worthwhile to attempt to try to create diversity in the soils, the slopes and the vegetation as a mimic of nature.
- **Drainage down old haul ramps**
  Haul ramps to dumps can be converted into drainage channels.
- **Infiltration into these coarse dumps limits erosion**
  Areas of coarse waste rock seldom have erosion problems because most of the surface water percolates. In some cases, coarse zones are created to enhance infiltration.
- **Loss of aquifer**
  In some areas, aquifers are mined out and occasionally, reclamation attempts to replace them (usually with poor water quality).
- **Microtopography with a backhoe, rocks, roughness**
  In some areas, microtopography is created by using a backhoe to dig out a shallow area and spread the dirt about irregularly. Rocks, pseudo-randomly placed can also be beneficial for wildlife, visually, etc.
- **Segregating surface waters**
  Clean surface water runoff on fill slopes is collected just above the toe and pipelined over the toe so it doesn't mix with the seepage water which needs to be treated.
- **Shotcreting of waste-rock dumps to limit infiltration**
  To prevent infiltration into waste rock dumps, some areas are shotcreted instead of being capped with soil.
- **Steep-walled channels for self-armouring by eroding banks**
  A channel may be designed with steep walls in bouldery ground. As the channel erodes, rocks roll into the channel, helping to self-armour it.

- **Watershed as an end land use**
  Similarly, an area of land may be deemed only suitable to be a part of a watershed, not contributing too much (or too little?) sediment or chemical loading. Other land uses would be secondary to this objective.

Biological

- **Avoiding fish**
  Some mines attempt to avoid having fish in some waterbodies for fear of triggering federal fish habitat regulation.
- **Bats and special wildlife, fed elk**
  Some mines are feeding wildlife to encourage them. Some are planting crops suitable for wildlife. Some special wildlife (bats) are being preserved through innovate reclamation designs.
- **Biosol (human sewage) to act as a fertilizer/organic amendment**
  It is common to dispose of human sewage from sewage treatment plants as an organic layer in mine reclamation.
- **Direct seeding of coal wastes**
  Direct seeding of wastes (with no capping topsoil layer) can be effective.
- **Dumps at repose can be revegetated.**
  Contrary to popular opinion, some dump slopes at their angle of repose can be effectively revegetated, particularly those with some cohesion.
- **Introduced species**
  Introduced species may overtake reclamation species, losing that aspect of the goodness of the reclamation species to overall stability.
- **Irregular limits for wildlife**
  The edges of the reclaimed areas should be left rough to encourage wildlife.
- **Planing mature trees upside-down to provide perching habitat for eagles**
  Uprooted trees plated upside down encourage bald eagles
- **Preservation of damaged areas**
  It is desirable to present some damaged areas as a reminder of what the site looked like in historic times. Ironically, these sites are being invaded by native plans and are reducing in size – they are in essence self-reclaiming, though slowly.
- **Reference areas**
  Most mines have reference areas for which they monitor biological activity so that the behavior of the reclamation plants can be compared to the natural system, thus taking the weather/climate change out of the equation. There is some controversy as to whether or not to fence the reference areas if the minesite is fenced (to avoid grazing of the reference area). Sometimes the mine expands to wipe out the reference area.

- **Rock piles for wildlife**

  Excess large rocks are not wasted but are piled up to create habitat for rodents and other mammals.
- **Shotgun seeding**

  Some mines use seed mixes with dozens of seeds in an effort to provide some initial diversity and to see what seeds catch.
- **Species diversity for long-term cover**

  By not having a mono-species reclamation plan, a diversity of specifies will allow different species to fill different niches, each adding its own stability, and should one specified die away (due to invasion, drought, pestilence, etc) other species will be able to fill some of the gaps.
- **Sustainability as an end land use**

  Perhaps rather than a feature of an area, sustainability as an end land use might be worthy of consideration. Under this scenario, the focus would be on creating sustainable (or stable) land, at the expense of other conflicting end land uses.
- **Underground tree nursery**

  Underground mines sometimes provide good conditions for tree nurseries – they are warm year round and often have abundant water and power.
- **Use of shrub islands for diversity and to aid in natural invasion**

  Use of island planting as a practical method of increasing diversity and minimizing costs and allowing self-design.

Land use

- **Aquaculture in old thickener and end pit lakes**

  Disused thickeners and end pit lakes may be ideal sites for aquaculture (fish farming).
- **Garbage dumps in mined out pits**

  Several sites have considered using the large mined out pits as garbage dumps. Though there may be environmental reasons against this, if the pit is a groundwater discharge this may be one of the best uses of the pit.
- **Jail as an end land use**

  One site was carefully considering a jail as an end land use. There are broad areas suitable for construction, there is power, water, and gas, and the site is relatively remote and easy to control access. Having prisoners work in crews to maintain the site has a certain appeal (though breaking rocks with a hammer is unlikely to be required).
- **Solar neutrino observatory**

  One mine in Ontario used the underground workings to create a solar neutrino observatory, taking the prize for being the most novel end land use.

Supplement D
Lessons learned

Closure planning and landscape performance at 63 Canadian and U.S. Mines

The following is a summary of lessons learned from visits to 63 minesites in Canada and the U.S. in 1996. Information has been compiled in various reports and presentations. The main goal of the mine visits was to determine the status of closure planning and how the reclaimed landscapes were performing.

Key lesson learned: Led by closure planning and landscape engineering, we are entering the initial stages of the next revolution in mining – planning and designing the closure landscapes. While most mines are doing excellent reclamation and are on the closure path, many would benefit from a more formalized approach to designing dynamic landscapes that are both reliable and predictable and that meet a variety of well-thought out goals and end land uses.

Lessons learned

1. Mines are generally doing well at reclamation. Most of the landscapes are being well reclaimed and are performing well, with the exceptions of hydrology and fine-grained tailings dyke slopes.

2. The mining industry is recognizing that reclamation is more than resloping and revegetation. Companies recognize that reclamation involves closure planning, resloping, revegetation, re-establishment of creeks and rivers, plant decommissioning activities and any ongoing maintenance and monitoring

3. Although regulatory goals continue to increase, corporate goals often are more stringent than regulatory ones. Presently, not all of the knowledge or tools are available to meet these goals.

4. Historically, mines have operated without closure plans. Most of the sites are small enough that they present little hazards to humans or wildlife but others are being reclaimed now at great expense. In most cases, costs would have been greatly reduced through developing and following a closure plan. In some cases, people would have avoided mining some areas that have proven unreclaimable. In some other cases, perpetual maintenance has resulted from lack of closure planning.

5. Most people believe landscapes are static which results in many mines presently focusing on creating stable landscapes. In reality, landscapes are dynamic and mines need to focus on creating landscapes that change in reliable and predictable ways. This is a major change in the philosophy of mine reclamation and is only achievable through the use of closure planning and landscape engineering.

6. Most metal mines disturb less than four square kilometres and typically about 10 to 20 percent is reclaimed progressively. Most metal mines have one pit, one or two rock dumps, and one tailings area, all of which are in use throughout the typical 25-year mine life.

7. About one third of operating mines visited were working on or had closure plans. Another third were close to closure and had decommissioning plans. Thus, most mines are on the closure path. Unfortunately, only one mine had actually turned land back to the crown.

8. There is a certification barrier – regulators are hesitant to certify land because of concern for long-term performance. Mines feel they have little to gain from certifying land, so very little reclaimed land has been certified.

9. There is a decommissioning barrier – because the long-term liability for reclaimed land is poorly understood, mines are hesitant about turning control of the land over to the owner.

10. Closure goals and land uses are generally poorly defined.

11. Long-term responsibility for the land is poorly defined and most mines have not considered the need for long-term maintenance. Unfortunately, for most large or difficult minesites, long-term maintenance will likely be required.

12. Closure is a difficult time for mines – employees are laid off and a lot of information and records are lost. Most mines go into dormancy, not fully reclaimed, unwilling to turn the land back to an owner who probably doesn't want the land back.

13. Mines are being required to post bonds or other forms of financial assurance for perpetual maintenance and this is a hot topic of negotiation for these mines. Means tests to determine the type of financial assurance are on the horizon, and insurance for long-term performance or catastrophic failure may also be in the cards.

14. Aesthetics of reclaimed and even active sites is becoming more of a concern to stakeholders and, therefore, to regulators.

15. End-of-pit lakes are common and their performance to date has been hard to predict. Lakes are filling faster than predicted and coming to different long-term lake level elevations than predicted. This is an area that needs greater research.

16. Highwalls are usually left unreclaimed.

17. Engineered covers to limit infiltration of water and oxygen into waste dumps are being widely used but their long-term performance (especially given cracks due to dump subsidence) is in question.

18. Mines are in the habit of promising too much from reclaimed landscapes – commitments made during permitting are often difficult or impossible to achieve.

19. Revegetation continues to evolve. Regulators are requiring native seed in many areas, direct seeding of mine wastes is a hot topic and microtopography is being employed as a method of getting moisture to plants and control erosion.

20. Hydrology is the number one issue for mine reclamation at the mines visited. Overland flow is not considered in the design of most dumps and tailings dykes, especially in Canada. Hydrology costs are often 10 to 20 percent of total reclamation costs. Most streams and rivers do not benefit from any design, much less the interdisciplinary design they need. There is a lot of confusion as to how to choose a design recurrence interval for floods. Blockages (such as beaver dams) or other degradations of the streams are not considered.

21. Landform grading, a hot topic at many mines, is being experimented with in various forms.

22. Mines are learning that it is critical to work with stakeholders during all parts of exploration, permitting, development, operation and closure. Mines need to develop better relationships with stakeholders, including regulators. They also need to provide more opportunities for the public to view reclamation performance first hand in an effort to build confidence that things are being done properly.

23. Landscape engineering is an emerging new discipline that will provide a better framework for designing landscapes that meeting stated goals. Closure planning, along with landscape engineering, are part of the next revolution in mining that will see long-term performance of reclaimed landscapes improve, and be more reliable and predictable too.

Supplement E
Lessons learned

Getting the most out of visits to other mines

Following are lessons learned about technical visits to mines. The information is based on visits to over 60 mines during 1996. You may wish to review this checklist as a guide for visiting mines, or to assist those who are visiting Syncrude.

Key lesson learned: It is useful to be well prepared for mine tours. By being prepared you can double the value of the tour.

Lessons learned

General comments

1. Visits generally have to be conducted in the snow-free period, typically on a weekday.

2. There are usually three types of informal tours offered — production tour, reclamation tour and plant tour. The type of tour depends on your guide and your interest. Typically tours take two to four hours with an hour of travel to and from the hotel.

3. It is important to specify in advance the reason for your tour and what you hope to see and learn.

4. It is usually best to limit the number of visitors to one or two. This makes things less formal, more personal and logistics at the mine are a lot easier. Two people allow you to compare notes after the visit. Try to make the trip as brief as practical, keep to the agreed times and make things as easy as possible for the person touring you.

First contact and arrangements

5. It is best to arrange the tour about one month in advance. After the first contact, follow-up with a fax to provide additional information about yourself, the reason for your trip and to confirm the arrangements made. Usually you will have to fly in or drive to the nearest town the night before.

6. Confirm dates, times and arrangements a couple of days before the tour. Directions to the mine can often be confusing, usually there is a dire lack of signs. Ask for a map (even hand-drawn), how long it will take to drive there, whether a car can make it and arrangements for getting through the mine gate. Ask about lunch arrangements if you will be there at midday. Eat a hardy breakfast and take a snack and something to drink — it may be late in the evening before you get somewhere that has food.

7. Ask for the name and phone number of a local hotel. Also ask where the closest airport or major highway is located, usually the sites are far enough off the beaten path as to challenge the travel agent.

8. A cellular phone is useful, but may not be in the zone of coverage at the mine site. Bring your own hardhat, safety boots and safety glasses. Also bring a change of shoes and clothes.

9. Bring a camera and film and be sure to ask if picture taking is okay (it usually is). Also bring a note book and pencil.

10. Make up a list of questions in advance and take the time to use these questions as a checklist. Ask for a photocopy of a map or an old mine plan to take home. Try to get a good picture that tells the main story of what you saw at the mine.

Touring and follow-up

11. Bringing some donuts, muffins, etc. to the mine is a great introduction.

12. It is important to send a thank you note (even by fax) when you get back to the office. Write the letter in a manner that ensures the tour guide will enjoy showing it to his or her boss. Be sure to follow up on any commitments. An invitation back to Syncrude is a good gesture.

Supplement F

Lessons learned

State of closure planning for new oil sands mines in 1997 [15]

Following are lessons learned from various meetings in August and September 1997 that give a good indication of current closure planning practice for new oil sands mines. Basically, there's a strong focus on ore production, meeting EIA requirements, and other planning for new mines with little emphasis on closure with the partial exception of Suncor for their new Millennia mine.[16]

Key lesson learned: Mine closure planning is fairly slow to catch on in the oil sands. Many of the new developments are focusing purely on short-term economics for their mine design with little effort on reclamation and closure landscape planning, likely because mines figure that reclamation and closure are details that are easy to handle later. Closure planning, in the sense required by BC and Ontario, is neither required by regulators nor being performed.

Lessons learned

1. Mines work on things that are either necessary for approval or have a cost benefit. Mines don't want to spend money on activities that take the environment beyond acceptable.

2. There is typically not enough time for closure planning of new mines under present timelines. A date is chosen for ore coming out of the ground. When one backs up the dates from this point, there is little time for mine planning, much less closure planning. In many cases, reviewers have more time than designers. Timelines do not permit any but modest regulatory delays.

3. "Maintenance-free" is poorly defined. To some it means the company will not be required to put money into perpetual maintenance (other than perhaps a bond). To me, maintenance-free means the landscape will forever continue to provide acceptable performance without human intervention. It is one of the few definitions that should be as clear to miners as it is to the person on the street.

4. There are several approaches to closure planning. The most common is to come up with the lowest cost plan, ignoring closure, then injecting closure into this plan and recycling. An alternative approach is to use closure principles to somewhat guide this original plan. Still another approach is to put closure first and design backwards from that point. Most oil sands mines ignore closure almost entirely during initial planning.

5. There are so many fundamental unresolved issues regarding closure planning that meetings often get off track. These unresolved issues include maintenance policy, end land uses, goals measurements, liability and change. Many of these could be covered off through a simple declaration checklist applied early on.

6. A useful plan is to think about generic landforms, assess them in terms of Environmental Impact Assessments (EIA) or closure, then fit them into the final landscape like a jigsaw puzzle. The hydrology is the lifeblood that connects them. Each landform produces, modifies or receives impacts from other landforms. This is a good way to look at impacts on an individual landform basis, or on an individual reclamation unit basis. It's interesting to note that almost everyone is thinking in terms of landforms now.

7. There could be a lot of composite tailings area in the region when all is said and done. Mobil is talking about building a dump on top of a composite tailings deposit.

8. There are a couple of useful thought processes to be followed. First, what would happen in the absence of any land use — what would be done, how does having an end land use cause us to change and what is the cost. Second, what would be done if closure or reclamation were not taken into account at all — what would the mines do and what is the cost difference to adopt reclamation and closure principles.

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[15] Information is based on 1997 meetings and discussions with Suncor and Syncrude and from listing to talks from the CIM District 5 Oil Sands Branch meeting in Fort McMurray in September 1997.

[16] It is interesting to note that one year later, there is a much stronger focus on closure design for oil sands mines, but there is still a long way to go.

9. There is a massive gulf between the disciplines of biology and geosciences (geology, geotechnical and physical sciences). There is also a gulf between mine planning, tailings planning and reclamation planning. We must work to reduce these.

10. There are such massive changes during the evolution of a mine, that the initial EIA basis will likely be different than that which finally gets certified. We risk being glib about this dichotomy and we risk losing the confidence of the public.

11. The EIA basis assumes a land which is stable (unchanging) geotechnically and geomorphically and even biological succession is a minor consideration. This is a fundamental flaw of the EIA basis and is starting to break down. Early on, mines focus on the EIA instead of on reducing impacts or long-term change.

12. Suncor looks at landforms as providing functions rather than being merely acted upon by the environment. This is an interesting concept.

13. A useful thinking exercise is to think about how the permitting process could get blindsided, and then take steps to avoid this.

14. Aurora has many areas greater than 600 000 to 900 000 bbls/hectare (60 to 90 bbls/square metre). These are rich and deep deposits. This land is incredibly valuable, and we can go to great lengths to mine such land.

15. Mine planning models divide the ground up into small blocks, 0.5m x 50m x 50m for Aurora. Generally, all waste blocks are the same. However, soon we will have to classify the different kinds of waste for things that it is good for (e.g. erosion protection, capping) and things that are of concern (e.g. sodicity, unsuitability for berms).

16. The Surmont in-situ project shows a competition between bitumen production and gas production. Work has gone on with the government to attempt to decide the optimum proportion of these two activities, and interesting and important exercise in light of the great uncertainties. Maximizing net social benefit is proposed, using a discount rate of 6 to 9 percent with sensitivity analyses.

17. There are about 10 in-situ (SAG-D) oil sands projects on the books. There would appear to be an opportunity to see how closure planning would apply to these projects, and what they might add to the cumulative impacts in the region.

18. Lease-boundary issues will be a major source of contention and potentially a major source of co-operation between the lease owners. Issues relate to pit locations, dump and tailings locations, drainage, and access.

19. Public consultation and working with stakeholders has become a significant activity for Alberta mines. Approaches are generally similar with some interesting differences. Having a good plan for working with stakeholders and a willingness to be influenced are important success factors.

20. Although closure planning may be a desirable activity to reduce costs and liability for a mining company, it is not presently required by regulators for permitting, and mines are having considerable permitting success with present methods.

Supplement G

Lessons learned

Lease boundary issues and shared infrastructure for operation and closure landscape design[17]

December 1998

The following some of the upcoming issues in oil sand development that relate to lease boundaries and opportunities for shared infrastructure.

Key lesson learned: While good fences make good neighbours, rigid oil sand lease boundaries could make for poor relationships between operators of adjacent leases. These artificial boundaries result in non-optimal mining and reclaimed landscape performance that, if managed poorly, could result in real costs or lost opportunity costs of hundreds of millions of dollars.

Lessons learned

1. Lease boundary issues are very complex. Although there are lots of opportunities, lease boundary issues are likely to cost each mine hundreds of millions of dollars as compared to if they were mining alone (and more if we fail to work together with other mines).

2. There are four categories of lease boundary issues, with several items under each – ore and reserves, waste disposal, closure / reclamation / landscape design, and infrastructure.

3. In many cases, mines will attempt to go it alone and remove their dependence or co-operation with adjacent mines on some issues (like building parallel dykes, finding unique ways to get water to the Athabasca rather than co-mingling, building independent infrastructure). This will continue but, when these inefficiencies sterilize ore and result in poorer landscape performance, the government will take a heavier role (perhaps the Alberta Energy and Utilities Board.)

4. Mining, waste disposal and constructing rivers at lease boundaries are emerging key issues.

5. There are many challenges in getting mines to work together. These include different timing of production and reclamation, different amount of resources to put to the project, different risk tolerances, individual personalities, different planning horizons, ever-changing plans, not wanting to agree to be bound to a plan, new information, differing regulatory requirements, lawyers and liability, desire to go-it-alone, and setting precedence and public expectations.

6. One main issue may be when the discretionary activities of one mine affect an adjacent one and how this is paid for or resolved. These types of activities may include putting waste at a boundary, not allowing a river to cross a lease, or changing the flow of a river.

7. In the same way that we are trying to optimize the "mechanics" of the closure landscape for our lease, we need to work this on a regional or sub-regional (watershed) basis. This is already starting to happen but there have been mixed results. As there are as many operational as closure issues, perhaps these are good places to start.

8. It seems clear that there needs to be an organizing body in place. The reclamation committee that is planned is a good start, but there also needs to be a more technical industry focus group put in place.

9. Now is a good time to start looking at these issues. The present negotiations between Syncrude and Shell on their common lease boundary are a perfect starting point in the evolution of this work.

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[17] Based on a short report in preparation and influenced by discussions with Dave Devenny. Many of the lessons are in a state of flux, being redefined and refined.

Supplement H

Lessons learned

Beaver dams and reclaimed landscapes

December 1998

The risks and influences of beaver dams on reclaimed landscapes was studied over the past several years. These lessons summarize findings from that study.

Key lesson learned: Lease 17/22 mining has disturbed hundreds of beaver dams and the reclaimed landscape will also have a similar number. Dams have the potential to cause considerable damage (flooding large areas, overtopping dam crests, outburst flooding) and there is historical precedence for all of these in North America. Although much can be done to reduce these risks, they cannot be eliminated.

Lessons learned

1. Just about every stream in northeastern Alberta has numerous beaver dams wherever there are stands of deciduous trees. There are hundreds of thousands of dams in the region. After near local extinction of beavers at the beginning of the 1900's due to overtrapping, populations have recently rebounded to historic levels.

2. Beavers (*Castor canadensis)* are aquatic rodents. They build dams to create ponds to provide protection from predators. In northern regions, the dams must provide deep enough water to keep the ponds from freezing to the bottom in the winter – beavers need access to food caches from underwater entrances to their lodge. Many beavers live in the banks of rivers. If the water is deep enough (in larger rivers or lakes) dames are not built.

3. Beaver dams are built by pushing sticks into the stream bed, and built up using mud and sticks (and rocks or anything else available). There s more mud on the upstream face to reduce seepage and more sticks on the downstream face to provide protection during overtopping. The dams are remarkably strong but can washout in floods – particularly when the dams are old and rotting. They fail due to overtopping or piping. They require constant maintenance and can be built or repaired in hours to days.

4. Beavers are "choosy generalists" when it comes to food. That is, they have a wide variety of food sources, but when possible, generally choose aspen, birch willow, and alder. They eat shoots and green plants in the spring and summer when available, but can subsist on the less nutritious bark during the rest of the year. They almost never eat conifer bark or cut down conifer trees. When it comes to building their dams, beavers use whatever wood is available on the ground – and most of what is available is the deciduous sticks left over from their feeding.

5. Beavers prefer clayey silt and silty clay (especially glaciolacustrine silts and clays) for dam construction material, but can use sand, organic rich sand, and even cattails to built their dams. Optimal soil conditions for beaver dams are present in the Lease 17/22 landscape in many areas.

6. Most of the natural topography of Lease 17 and 22 has a 1 percent slope which is ideally suited to beaver activity. Beavers can be expected to dam creeks with slopes up to about 7 percent slope.

7. Numerous three metre high dams were observed in the region and the literature records some dams to 4 metre. The highest dams are in steep-walled creeks. For broader floodplains, dams to 2.5 metres high are more common, and in very wide floodplains, dams are less than 2 metres high. In most cases, beavers sense the diminishing returns of flooded area verses dam height and only dam to heights that are practical.

8. Landscape designs must accommodate beaver dams for most areas. Passive measures include designing creek channels to allow beaver dams without causing widespread flooding or redirecting water courses into unintended areas. The stream channels should be deep enough (>3 metre) with a pilot channel and floodplain. Design for erosion should consider multiple breaches of ponds during flood events.

9. Beavers will dam spillways and the outlets of lakes so freeboard needs to be enough to withstand this. In particular, a constructed wetland might be susceptible to beaver damming at its outlet.

10. Passive measures to discourage (but not necessarily eliminate) beaver dam activity in critical areas include use of rock drains, placing substrates that discourage deciduous vegetation, ensuring water in channels remains more than 4 metre deep. Strategies such as trying to construct channels wide enough or with high enough

discharges are unlikely to succeed. Where possible, avoid side-hill drainage schemes.

11. Beavers do not dam ephemeral streams but it is not clear at what annual discharge threshold beavers will start building dams.

12. Active beaver control methods (a form of perpetual maintenance) includes trapping or shooting on a regular basis, vegetation control in an 80 to 100 metre zone around the channel, fencing and weirs, and beaver dam removal.

13. The following is suggested as the most practical strategy. Where practical, construct stream channels and lake outlets to accommodate beaver activity. In critical areas, passive design measures to discourage beaver activity should be employed and backed up with beaver control. The design in these cases should allow some beaver activity for several years between inspections (that is, the landscape should be designed so that a single dam constructed in a single season should not cause significant damage).

14. For areas that have the potential to be aggrading (particular streams subject to aeolian or fluvial solids loading) this progression of aggrading beaver dams must be considered. At the outlets of lakes, the water should be largely sediment free making aggrading beaver dams less likely.

15. Streams that parallel escarpments can cause landslides which in turn lead to stream avulsion.

16. Beaver dam blockages of reclamation creeks is a significant hazard to many mines yet is seldom taken into account.

17. The following are some interesting facts and statistics:

- Four of 29 lakes more than one kilometre in length in the oil sands region are dammed by beavers at their outlets.
- Most beaver dams in the region are overtopped safely for weeks every spring.
- Loss of several beaver dams (cascading dam failures) is common and results in short, high discharge flood events.
- Beaver dams have caused tailings dam failures, train wrecks, town flooding, and highway deaths.
- Beaver lore is often incorrect: beavers are not really devils, not the highest ranking organisms behind humans, they do not usually arch their dams upstream, they do not preferentially fell trees towards the water, they do not only react to the sound of running water, and they are not always busy.

Supplement I

Lessons learned

1996 multilateral exchange workshop on

mine decommissioning and custodial transfer

June 1997

Following are some of the opinions and key lessons from the Multilateral Exchange workshop attended by Gord McKenna and Wayne McKee. The workshop was run in Vancouver on June 5, 1997 and involved about 40 people from around the world including regulators, consultants, and mine owners. The focus was on decommissioning of uranium mines, but almost all of the talks were of a general nature and applicable to Syncrude as well. Talks were 10 minutes each, which worked well, but would work better if people were a little better prepared to talk for such a short of time. There was very little opportunity for discussion. Virtually all of the points raised seemed to have wide acceptance.

Key lesson learned: Closure planning is a crucial element for mines with difficult conditions. Considerable expertise has gone into developing closure planning as a tool, and much can be learned from others experience. Syncrude has learned a lot in a short time, and has a lot to contribute to such discussions, and also much to learn.

Lessons learned

Planning and closure

1. The industry should consider a more positive slant on closure plans by using a title such as "Sustainable Land Use Plans."

2. Closure definitions are often vague. We need to build some more robust definitions.

3. Walk-away is well defined as the situation where no future human interference to ensure environmental protection and human health and safety.

4. Mining companies could retain land after closure, with subsequent land uses that generate revenue to offset maintenance / remediation costs.

5. Time frames of 200 and 1000 years being widely used. People are unsure of how to take into account inevitable long-term climate change and cycles.

6. Closure issues can be broken down into technical and socio-political. We have advanced the technical aspects well beyond the socio-political.

7. The lessons learned format of reporting information can be useful.

Closure cost

1. Higher levels of confidence in landscape performance are exponentially more expensive.

2. Economic assessment of closure options should use discount rates that are applicable to the activity. Where there is a burden on future generations or known residual liability, 0 to 1 percent may be applicable. Where there is a routine maintenance item, the discount rate is the cost of money (3 percent). Where possible, the analysis should also include the devaluation of resources where a value can be put on it.

3. By one account (Andy Robertson) the real rate of closure cost escalation (due to regulatory changes) is about 16 to 20 percent per year over the last 20 years and can be expected to continue escalating.

4. There is a fairly well supported opinion that royalties paid during operation should be used in part to create a fund for society to pay post-closure costs. In particular, governments should pick up the tab for regulatory changes, not the mines.

5. Use of institutional controls in many cases reduces reclamation costs by a factor of 10 vs that of a supposedly walk-away scenario.

6.. Closure funding (requirements for financial assurance) is difficult and onerous and likely being poorly implemented.

Regulatory environment

1. Solutions for closure are site specific and we need to avoid broad-sweeping codes.

2. It is unlikely we can create a landscape that is totally self-sustaining. It may also be undesirable to attempt to do so because there may be a possibility of missing an opportunity to create ongoing commercial/ recreational opportunities. The industry needs to work on regulator's

understanding that attempting to return the land to the original state is usually unreasonable. There seems to be general agreement that "self-sustaining = walk away" is not just unlikely but seen to be impossible.

3. In one recent Australian case, an arbitrator was used to get agreement on closure performance measures between the government and a mining company.

4. The U.S. has a significant number of challenging uranium mine/mill sites under remediation. The approach is one of containment, monitoring, stewardship, and withholding land from significant subsequent uses.

5. Governments and landowners are concerned with hidden defects, extreme events, and changing retroactive liabilities. There is growing recognition that government/ society is the ultimate steward of the land.

6.. The level of severity of environmental regulation is often coincident with the viability of an industry — profitable industries are faced with harsher regulations.

Technology

1. There is general acceptance that changes will continue to occur in technology, regulations, climate, etc that will devalue today's attempts at remediation and containment. There is also a strong expectation at many mines that remining will occur in the future. Together, this would suggest implementing cheaper solutions instead of more expensive ones, avoiding pre-empting future technologies, and that it is very difficult to accurately predict post-closure costs into the future.

2. Science of design and construction of covers and liners is well developed, but there is disagreement on the effectiveness of these measures. Work continues in trying to better understand the various flux mechanisms.

3. There are differing opinions on the extent to which vegetation can pump contaminants from the containment zones through a cover. One opinion suggests that the aesthetic/ erosion control value of vegetation far outweigh the containment transport.

4. Contrary to many statements floating about, closure landscape design should be viewed as an immature system, not a climax system.

5. Wetlands can remove some dissolved solids successfully. Some operations have designed unnatural wetland mazes that force a longer flow path and are essentially externalizing a vessel.

6. Beaver activity is being deliberately designed into a landscape to create wetlands and to control erosion.

7. Natural analogues are being considered here and there but not systematically.

8. A classification for three levels of fluid containment is proposed:

- artificial above grade
- artificial below grade
- geologic containment (rock-rimmed lakes and at the bottom of deep lakes).

Risk / modelling

1. People shouldn't forget risk analysis usually comes down to choosing between one option and another. It is not an end in itself.

2. Sites with restricted access usually have lower risk than those with unrestricted access.

3. Sophisticated modelling capabilities exist to compare probably impacts of various options, but there is a lot of scepticism on its value. Usually the mechanisms are not fully understood, yet great precision is reported. Risk models, in particular, are susceptible to unknown unknowns.

Supplement J

Lessons learned

1997 B.C. Mine Reclamation Symposium[18]

October 1997

The following is a summary of key features from the BC Reclamation Symposium that I think are interesting to Syncrude. The symposium is well attended (200 people) and well supported by governments, consultants, academics and the mining industry. Many of the papers focused on research-related work; it would be interesting to see a few more case histories. Overall, the calibre of papers is high and the symposium is an excellent forum and meeting place.

Key lesson learned: Closure planning is a very hot topic and reclamation is becoming more and more sophisticated.

Lessons learned

1. In many cases, extraordinary measures are taken to get plants to start growing or to protect young plants from wildlife. It is not always clear that these plants will be self sustaining, especially in terms of propagation. We need to be more upfront about the reasons why they will be self-sustaining in the absence of careful seed preparation, seeding or planting, fertilizing, irrigating, the application of herbicides and pesticides, and plant protectors.

2. Quintette Coal has an interesting 'native species island program' for its high elevation mine reclamation. Agronomic species are used in most areas to provide early erosion protection and to act as a nurse crop. Native seed islands cover 0.2 to one hectare each and are distributed randomly to initially cover four percent of the reclaimed area. There is not enough native seed to cover everywhere. A computer model is used for the dispersion and expansion of the native plants out from the islands. Up to 15 metres of expansion has occurred in three years and the volunteer plants have very high survival rates after they germinate. Modelling shows the process is on track for the requirements of succession within 20 years. This is an excellent example of economics, science, practicality and self-design. It has many of the features of a successfully employed performance indicator.

[illegible] Use of innoculants, such as mycorrhizal fungi, are becoming more common as we better understand the ecosystem and relationships and attempt to give reclamation plants a stronger start.

4. Bullmoose Coal Mine is purposefully encouraging infiltration to control runoff from haul roads. Haul roads are reclaimed differently so as to serve as wildlife corridors.

5. Chile is looking to implement reclamation, environmental, and closure regulation and is seeking Canadian assistance. Mining is a large component of their economy so they want to bring in regulation carefully. Closure plans will be required for permitting, but must be three pages or less. There are problems with implementing a system for existing and small mines.

6. People are finding it important to monitor and document the invasion of plants from one reclamation area to another and onto the site from the surrounding natural areas. This is part of "sustainability monitoring."

7. The time is ripe for reclamation performance indicators (RPIs), especially to demonstrate the sustainability of revegetation. There is some work underway on RPIs, particularly for when fertilization is stopped and for adding organic materials such as human sewage to the landscape (biosols). One mine has successfully used biosols to convert a tailings area into a municipal golf course.

8. We should consider an official employee hosted eco-tour route at Syncrude, complete with a map and signs.

9. Covers for rock dumps are complicated and have low long-term predictability.

10. Consultants need to be careful about photos of mines. Too often they are unflattering or highlight temporary deficiencies. The same goes for demonstrations of geographical information systems (GIS). It becomes awkward for everyone. Mines need to provide better photos to consultants.

11. For mines, GIS is becoming a requirement for reclamation and closure. Software and hardware are typically 15 percent of the total cost, the rest is database development and keypunching. Development time is usually between 12 and 18 months. There is a lot of emphasis on very

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[18] 1997 BC Mine Reclamation Symposium, Canadian Land Reclamation Association Symposium, Cranbrook British Columbia

simplistic ecomodels for GIS, but most of the power resides with good storage and presentation of data.

12. Forestry reclamation has many parallels to mine reclamation except that for a forestry reclamation job, there may be hundreds of sites are less than one hectare. A cost benefit analysis would suggest not to do much work (even replanting), but reforestation allows other areas to be cut as a way of internalizing speed of reforestation. In this type of work, the key is surface-water drainage, even on the small sites.

13. Biotechnology is becoming fairly advanced to small site-specific areas but still lacks the proof of concept for large mining areas. Willows are the main plant used. There is the term successional reclamation, which may have some power for us. At Syncrude, I believe we have enough literature and on-site know-how that we should manage bioengineering by ourselves instead of trying to find the right consultant. We know what we want and what we can do.

14. There are over 100 definitions of sustainability, many of which are mixed up with biodiversity.

15. The biosol people have provided very prescriptive algorithms for design and monitoring of the use of biosols. While I think the system is flawed because it is overly detailed, there are some very good ideas and thinking we can adopt, particularly in the monitoring programs.

16. Increasingly, mines are taking stakeholders on tours of other mines. This helps to form stronger bonds and develop trust between stakeholders, regulators and the mines.

17. Some mines are adopting a philosophy of conservatism in their reclamation. These mines say to management, if we are too successful we can always back off.

18. Mines need the thinking that goes with closure to build their \framework. There is a lot of utility in sharing knowledge. The industry must realize there is no silver bullet or cookbook approach – the right answer differs from mine to mine and time to time.

19. We had some discussion about mine closure. Often there are layoffs and, later, rehiring but typically the mines don't hire everyone back. This leaves a lot of disappointed people in the community. While a massive public relations program is required, even the best program will not be fully effective. At closure, there are no longer people like accountants and purchasing agents to write checks – everything slows down.

20. Here's an interesting perspective on providing mine closure to a number of mines within a company. It may be too difficult to make much change (pro-act) or design for closure. Instead, concentrate on bringing on new technologies to help solve problems. Help the mine ensure it has the correct management systems to deal with the problems. In some cases, it is necessary to explain to the person at the mine, that by giving them the knowledge, they are the new responsible person in charge. For example, if there is an environmental incident, they could be the ones in court and going to jail. Should that happen, the only defence is that things happen, you can't say you didn't know or it was too expensive.

I think that not trying to pro-act is probably not a defensible position, but working towards the lofty goal of pro-acting must be able to save some money and reduce liability in the long term. Perhaps mines need to be shocked by the remediation cost of a problem to show them the light when it comes to closure planning.

Supplement K

Lessons learned

Mine Planning and Equipment

Selection Symposium 98

October 1998

Following is a summary of lessons and ideas gained from the MPES 98 Symposium in Calgary. I attended thirty-five presentations — here are the common themes and some useful points. The proceedings have a lot more information for those interested.

Key lesson learned: Mines world-wide are facing declining commodity prices, declining ore-body quality, and increasing production and environmental costs. For the past twenty years or more, mines have been in a continuous improvement phase and are now looking for breakthrough technologies. Promising breakthrough technologies involve hydrotransport, robotics (automation), near-face extraction (where only a concentrate leaves the mine area) and closure planning.

Lessons learned

Mine production and equipment

1. Mining is high tech. There is a high level of research and development and training in the mining industry. Canada is a world leader in mining R+D.

2. Mining has some very significant challenges presently – low commodity prices, increasing capital and operating costs, diminished reserves (especially those easy to mine) and increased environmental costs.

3. There are a lot of high-power government and industry alliances out there. Electronic publishing is facilitating communications. Syncrude should see if additional alliances would be worthwhile.

4. There is a lot of high-level management introspection on technology development in mining. Mining in the last 10 to 20 years has been in an incremental / continuous improvement mode utilizing a few dominant technologies. A lot of improvements are being made presently, but we will soon be in the era of breakthrough technologies.

5. Hopes for breakthrough technologies are mostly pinned on automated technology (robotics, especially for underground mining), massive reduction in waste movement (by leaving waste near the ore face) and perhaps closure planning.

6. Mines need to organize their organization to take advantage of changing technology. Many people have thought about the role of development in the mining industry – it would be worthwhile for Syncrude to review what others have learned in this area – particularly in bringing technology into operations.

7. Workforce training is an essential component of having a high-tech industry and mining has high levels of training compared to other industries.

8. Real-time mine information systems need parallel performance management systems to act on the data and make it useful. As systems develop, Syncrude should further review how this information is being used in the field (by supervisors) to see if it could be made more effective. Maybe there is a split role for more technical supervision versus more people supervision.

9. Lack of infrastructure in many developing countries severely limit mine development, particularly of medium-sized mines (only large ones can be developed due to the massive capital required to build the infrastructure). Exploration is also hindered.

Reclamation and closure

1. There is great interest in reclamation and closure among miners, but less among equipment suppliers and software companies.

2. People are doing a lot of good thinking about reclamation philosophy and practical solutions are slowly emerging. There is a lot to be learned from the practices and ideas of these mines and their consultants. There are unfortunately a lot of people reinventing the wheel around the world, even on ideas such as putting topsoil on top of waste. There needs to be better communication about reclamation – perhaps some better textbooks.

3. There are those who believe that soft rock mines (oil sands and coal) have an easier job to implement closure planning and landform grading than do hardrock mines. Interestingly it is likely more important to hardrock mines. Some other miners see Syncrude as doing a Cadillac job of reclamation, although internally we feel our efforts are at the right level and reasonably efficient for the most part.

4. End-pit lake slope stability is or will be a common issue for most mines. This applies to both ravelling / rock fall hazards as well as large landslides. There should be a special international workshop on end-pit lakes, perhaps organized by Syncrude in 2000.

5. Continue surface miners might have an application for creating drainage or picking up reclamation material (but probably not).

6. People are celebrating the successful reclamation of 10 to 100 hectares, especially for underground mines. Syncrude's 20,000 hectare to reclaim is obviously a completely different scale.

7. A lot of mines have everything working against them for reclamation and have a hard time at it. At Syncrude, almost everything is working for us, yet we have a higher standard to meet, so there seem to be self-levelling mechanisms for the level of technical reclamation challenge facing many mines.

8. There is SMCRA legislation in the U.S. that is highly prescriptive but may contain useful ideas for landscape engineering (if taken *out* of context).

9. Many mines are using artists' paintings to depict closure landscapes.

10. In most areas of the world there is significant population pressure on reclaimed lands.

11. Closure for one French potash mine involves washing of the waste salt piles into the Rhine River at rates of thousands of cubic metres per minute of brine wastewater.

12. One mine has an interesting program using columns and gypsum treatment to study counteract a salinization problem.

13. Kennecott Bingham Canyon is using sprinklers for dust control on its tailings pond. This might be of interest to Syncrude. (The Bingham Canyon tailings pond is reportedly 2600 hectares – it might be bigger than Syncrude's Mildred Lake Settling Basin!)

Geotechnical engineering

1. Most mining geotechnique seems to focus on rock mechanics for underground mining (ground control). The field is dominated by theoretical and numerical rock mechanics.

2. High-level rock mechanics is increasingly done by numerical specialists with little appreciation for geology, hydrology, mapping, or field conditions. This is problematic.

3. Three-dimensional stress-strain modelling is become more common but is expensive and the usefulness of sometimes questionable.

4. Software used for predicting subsidence (even that over underground workings) may be of interest in predicting long-term dump performance.

Mine planning

1. Some mine planners are leaping to optimization programs for mine planning without a basic screening and understanding of the more basic aspects of design of plans for particular deposits.

2. Mine planning software for choosing ultimate pit limits is very complicated and sophisticated numerically but requires manual adjustment of results for geotechnical and other basic constraints. Because planners rely on these tools and because closure considerations are not built into the software, they are not well considered in selecting ultimate pit limits. We need to get closure considerations built into this kind of software or process someday to allow people to better address closure issues in design.

3. Risk analysis is not being well handled by mine planning software. So although these models provide a lot of information and seem sophisticated, they are actually rather rudimentary and require a lot of judgement to use and even more to make the actual decision. They are ore-driven rather than waste driven (it is assumed the waste is simple and can be simplified by a profile of haul distances). This seems rather simplistic for any mines, but especially mines that are spoil-bound.

3. What is missing perhaps in the software, is highly interactive software that allows a good mining engineer to use their judgement more by supporting simple calculations.

4. There is a general recognition that long-term mine economics are poorly handled and that

Discounted Cash Flow analysis is a poor tour for long-term projects. Mine and project economics are being viewed more statistically using simple Monte-Carlo analyses, but even these are rather crude tools. When doing this type of risk assessment, the discount rate should be the real rate, rather than the risk adjusted rate, because the risk is being estimated by the statistics. One could back out the equivalent risk discount rate from the results.

5. Block value models are being used to store and model more and more information (geotechnical, chemical, etc). This can be especially important for waste materials too. Syncrude should review what information is gathered for the various blocks and see if more should be done. In particular, information about the processibility of the ore could be important, and characterization of some of the waste materials (salinity or sodicity).

Supplement L

Lessons learned

Effective public consultation meetings

June 1998

Public consultation, and effective stakeholder consultation meetings, is becoming increasingly important for mining companies. Syncrude has run several public meetings on reclamation and tailings issues. Typically, the meetings run six to eight hours with between 30 and 60 participants. The following is a collection of lessons and observations made at several public consultation meetings regarding mine reclamation, land use and closure.

Key lesson learned: To effectively gain support and buy-in from stakeholders, and to meet regulatory requirements, public meetings for closure consultation have become a necessity for mining companies. Providing stakeholders with periodic updates and sharing all information freely and honestly are excellent strategies that help to demonstrate corporate sincerity, competence and the value of stakeholder contributions.

Lessons learned

Participation/attendance/set-up

1. It is difficult to attract members of the public to attend public consultation meetings. The list of participants is usually much shorter than the list of those invited.

2.. Public consultation meetings are an effective vehicle for communicating among Syncrude staff. They provide a good opportunity for the operations employees to become informed about the activities of the research and development employees.

3. The same people usually come to most of the meetings. Syncrude always has a large number of staff attending. Usually, the next biggest group of participants is from Alberta Environmental Protection — about six to 15 regulators participate. A couple of representatives from Suncor also participate.

4. It's helpful to find a neutral and central location to hold the meetings. The Oil Sands Discovery Centre has been a good choice.

5. Signing people in is a good way to welcome them and ensure their contact information is recorded clearly. Obtaining a business card from participants is extremely helpful.

Process

6. It is a good idea to set clear ground rules and clarify meeting outcomes at the beginning of the meeting to avoid any confusion later on in the day. For example, it should be established that the meeting will only deal with closure matters. Any other concerns will be recorded and passed along to the people at Syncrude who are affected.

7. It's important to set the stage and provide context for the participants. That ensures everyone is starting from the same point. Having a member of management speak on behalf of Syncrude and be accountable for the meeting's outcome, goes a long way in establishing credibility for both Syncrude and the process.

8. It is difficult to keep the schedule on track. First of all, people never seem to return to the meeting on time after a coffee or lunch break. Secondly, the agenda is usually too full, probably because the day is multidisciplinary and there is a need to accomplish a great deal. Instead, the agenda should perhaps allow for longer breaks that can then be cut back if necessary.

9. Presentations usually run a little longer than planned and questions from stakeholders often take much longer than anticipated. It is difficult to guess the areas of special interest before the meeting.

10. Meetings are often dominated by a few stakeholders. It's important to ensure the facilitator is able to encourage participation from all stakeholders.

11. Recording all the concerns on a flip chart is a useful way to assure the audience that their thoughts are being heard and recorded. This is an important step in gaining support and commitment from stakeholders. It's also critical that comments are recorded as stated without passing judgement on them, and these flip-charts are transcribed in the proceedings.

12. Often times the stakeholders are talking to each other as much as with Syncrude. While this can be a positive thing as it builds relationships

among stakeholders, it can also be disruptive to other participants.

Communication

13. An emphasis should be placed on effectively communicating to the audience. Instead, presenters often make the mistake that participants fully understand mining, oil sands and Syncrude in particular. For example, presentations should avoid jargon and acronyms and strive to keep things simple and concise. To show the audience what is meant, clear and effective visuals, like maps or photos, are helpful whenever possible. Visuals also help to support a message and keep the viewers interested in the presentation.

14. The quality of the presentations and overheads is usually very good. Having those involved in the work present findings in their own format and style, enhances credibility and immediacy to the work. It also provides valuable experience for the presenters.

15. The questions from the stakeholders are usually very good, although a greater emphasis could be placed on learning how to more effectively answer questions and address concerns. It always helps to at least be as well informed as the participants so questions can be answered quickly and confidently.

16. Following the meeting, putting together a complete proceedings, including the questions and answers, is a good way of ensuring that discussions get recorded and distributed.

Supplement M

Lessons learned

A highway reconnaissance of

Central Alberta landforms and slopes

January 1999

In May 1997, I travelled with Horst Schor and Richard Dawson to various landforms around central Alberta as a reconnaissance trip. The goal was to find places to return to do more in-depth study of erosion processes on slopes, and to examine things that could be useful for Syncrude's reclamation process, including landform grading. The trip was very successful, a photo-filled report issued, and the following lessons learned from this trip.

Key lesson learned: Slope erosion in Alberta is due to an complicated interaction of near-surface phenomena, mostly due to shallow groundwater flow in rainstorms, but also affected by weathering, frost, vegetation, and a host of other effects. Because it is so complicated, study and prediction of such phenomena is probably better handled empirically and statistically rather than based on fundamental forces and processes.

Lessons learned

Reclaimed sites

1. The new sinkhole at the Ellerslie abandoned mine is a real example of physical hazards in abandoned mines in Alberta. Similarly, the beaver dam across the Whitemud Creek there is another real example of beaver dams blocking streams through mined areas.

2.. Several reclaimed sites were having problems with erosion from off-road vehicles. This could prove to be problematic for any open (unforested) reclaimed landscape that is not policed.

3. Abandoned coal-spoil piles from over 100 mines near Drumheller have almost all been remined for red patio rock —a study of the remaining spoil piles might prove fruitless. There has been problem with spontaneous combustion and concern about people falling into burnt-out shells. Some livestock has been lost in this manner.

Landform grading at Highvale

4. Highvale's sight and sound berm, composed of dragline spoils from the boxcut opening, was build previously to look like a dam, with constant 3H:1V slopes and had a very engineered look.

5. Now, they use a landform grading approach where they put in toe and crest stakes and allow the operators to field fit a rolling topography with ridges and swales, keeping to 3H:1V overall. The results are remarkable.

6. They are planting trees in the swales (where there is more water) and grasses on the ridges. Some of the trees are being spaded in – an economical alternative on a small scale that help jumpstart the reclamation results.

7. There has been good performance of the landform graded areas. Hydrology was not taken into account explicitly during design, but the watersheds are small enough that performance is okay.

8. Pipelines, roads, existing ditches, and lease-boundary constraints are all linear influences that makes it harder to get as much variation in toe position as one might like.

9. Because of the reduced engineering, staking, and other requirements for this work, regrading costs are 30% cheaper using landform grading than the traditional straight-line / planar approach.

10. On a related note, Transalta puts reclamation money into a sinking account that can be used by other areas of the organization on a short-term funded loan approach.

Ridgelines

11. A key element of the visual aspects of landform grading is ridgelines. Traditionally people use flat-topped dykes and dumps which can give a very engineered approach. Adding "roughness" can create a more natural appearance.

12. Alberta landforms show a variety of ridgeline roughnesses. A simple subjective rating system is proposed and a measure of roughness (defined as the typical relief of the roughness as compared to the total height of the landform) is a fairly good and very simple measure.

13. Based on simple computer graphics and reviewing photos of natural Alberta ridgelines,

landform grading should target roughnesses of 10-20% to avoid the engineered look.

14. A variety of very simple design techniques to achieve greater roughness for aesthetic reasons are presented. While purely an aesthetic function, these elements can be added during landform construction for little or, more likely, no cost.

15. Some areas with almost zero roughness (e.g., prairie-level peneplains at the Drumheller badlands are very flat viewed edge on) have a greater visual roughness when viewed near the toe because gullies cut into the peneplain and create roughness for the observer. The same is true of the Athabasca valley margins near Fort McMurray and is an important element in design of landforms.

Other landform grading examples

16. Alberta has lots of good scenery that can provide inspiration for landform grading elements and design.

17. Initial investigations into "direct copy" landform grading where suitable topographies are copied directly for use on reclaimed landscape has had mixed results. One would of course have to ensure that the copied designs are suitable for the application and materials at hand. But overall, it would appear that the natural system is too complicated, and that more should be left for field fitting.

18. However, direct copy of elements and shapes of natural topographic features (such as swales) could be a very powerful tool. Areas of interest include Longview Hill, Nose Hill (Calgary), and an area near Drumheller on Highway 9.

19. If the landform-graded topography is too subtle, trees will quickly hide it. The physical performance would still be fine, but aesthetic gains are reduced (unless different vegetation grows in the swales versus the ridges). Low mountains in the Rockies and foothills show that swales and ridges, if bold enough, are not obscured by heavy forest. A first guess at how much relief is needed to avoid being obscured, based on observations in the field and of the S4 Area at Syncrude, suggest that the swales need to have a depth of about ½ to ¾ of the height of mature trees. More work on refining this estimate would be useful and easy.

Micromechanics of slope erosion

20. One of the major goals of the trip was to investigate the micromechanisms of slope erosion to see if this would make a good thesis topic. What I found is that the mechanisms are complex, interrelated, somewhat random, temporal, and overall pretty complicated.

21. The mechanics of slope erosion are not due so much to overland flow as throughflow – the shallow ground-water flow that occurs in a shallow high-permeability zone, typically in the upper 30 to 100 centimetres of a slope.

22. This zone is caused by weathering (mostly frost, but also dessication and vegetation) or by the presence of topsoil over a less permeable layer.

23. Minor changes in permeability on 10 cm by 10cm basis seem to control much of the flow, much of the exit seep-age, and hence much of the slope performance.

24. Slopes cut to a particular uniform angle typically show a wide range of erosion performance from good to poor, likely due to minor variations in geology.

25. If one starts to look closely at the mechanisms, one can see that individual plants or boulders can have a considerable effect on erosion of a slope. In the case of the boulders, the fact that they are heavy (dense) and impermeable elements is important.

26. Self-armouring of slopes is only possible if the rock remains on the slope when it is exposed. Usually, the rock slides or rolls off to the toe. Sometimes, the rock is weathered rapidly and breaks up.

27. Where clays are present on the slope, they are prone to dessication, becoming highly permeable and erodible.

28. There is an opportunity for a more statistical approach by mapping long linear routes – stopping to map every exposure that meets some pre-determined criteria. High-ways are an obvious target and candidates based on this reconnaissance include: Highway 93 (, Jasper to Saskatchewan River Crossing), abandoned Highway 93 ("the old road" north of Saskatchewan River Crossing), High-way 11, (David Thompson Highway between Nordegg and Saskatchewan River Crossing), Coquihalla Highway (north of Merit, BC), Highway 63 (between Wandering River to the Barge Terminal, north of Fort McMurray),

Highway 3 (through Crownest Pass), Coal Mountain Access Road (Sparwood BC).

Slip-of failures along slopes

29. Numerous slopes have shallow slip off failures. The morphology is relatively constant. The sliding plan is located either at the base of the root zone or the weathered zone – in both cases, where there is a strong decrease in permeability, typically 0.3 to 0.8m below the ground surface.

30. Most slip-off failures occur along road cuts and the outside bends of creeks and rivers.

31. Not all portions of the slope are subject to this failure mode – local variations seem responsible – most likely the influence of seepage concentrated in a few areas. Rather than traditional groundwater seepage, it is likely due more to throughflow (seepage through the higher permeability layer parallel to the slope).

32. Slipoff failures occur on slopes ranging from as low as 8H:1V up to 1H:1V.

33. The mechanisms of this kind of failure seem to be complex and highly temporal.

Badland slopes at Drumheller

34. Expected that the dispersive clay slopes in the badlands region in Drumheller would provide a good opportunity to study slope erosion mechanisms that may become important at Syncrude.

35. There is lots of literature on slope erosion in badlands area, include Alberta badlands (alas from Steveville badlands about 100km from Drumheller – similar but not exactly the same).

36. There is good access to lots and lots of badland slopes in the Red Deer River valley at Drumheller. It is best to go on the slopes in dry periods because he wetted slopes become very slippery (due to the bentonitic clays). However, it would be very interesting to observe the slopes in a big rainstorm to see the water in action.

37. The area's geology is mostly interbedded sands and weakly cemented sandstones, bentonitic clays, coal and ironstone beds. The units are remarkably continuous over wide areas. Comparison of the same layers in different areas would be possible.

38. Erosion rates in the badlands are high – estimates of 5mm per year of slope retreat seem reasonable. Most of the sediment is washed down to the Red Deer River making it very muddy. There are almost no layers of dispersive clay debris – it seems to have been all carried to the river. There are fine sand fans, but even these seem very small for all the erosion.

39. Most of the slopes are rilled and gullied and exhibit specific textures such as pipe holes, ropy sand textures (due to rills), popcorn weathering of bentonitic clays, small fans, depressions and sinkholes.

40. The erosion of the slopes is a complex system – the sands and clays seem to erode at the same rates – there is no preferential steepening of the slopes due to these units. The sands erode by weathering and loss of cementation, largely from shallow groundwater flow (interflow). The sands are especially prone to piping. The clays erode through dessication and dispersive clay dissolution. Ironstones, jointed and cemented siltstones, and coal layers provide greater resistance and localized steepening and flat plains (small peneplains).

41. In most slopes, erosion is occurring faster than the arid vegetation can keep up. Flatter slopes have more vegetation and little erosion.

42. Actively eroding slopes typically have a weathered crust of 1 to 2 centimetres thick. Larger semi-vegetated slopes have a crust / loose zone of about 0.5m. Passive slopes are darker, more vegetated.

43. Gullies extend up to peneplains, including to prairie level. It is not clear whether they migrate from the bottom up or the top down, but piping plays a role in just about all of them. The valley wall slopes are dissected by large gullies, which typically run diagonal down the slope, creating distinctive pyramidal shapes.

44. At the head of gullies are characteristic depressions of all scales (from a hundred metres to a few metres) which have caused and are causing the gullies. Their enlargement feeds more and more water to the gully area. This creates a characteristic scalloped topography along the river valley crests – very similar to the Athabasca and Clearwater (and other) River valleys in the Fort McMurray region – the processes are likely similar.

45. It would be interesting to do some broad statistical work on these slopes – on mapping the

field stability curve, and including in this the stability against massive erosion. Secondly it would be interesting to look at the entrance and exits to pipes on slopes to get a better handle on where they are occurring and why.

46. There are numerous natural terraces (of the Red Deer River) in some reaches of the valleys. These are dissected by the gullies, but give an indication of erosion rates of these gullies and rates of gross slope retreat. These could be compared to the estimates based on pin measurements on the slopes.

Supplement N

Lessons learned

Artist's renditions of closure landscapes

January 1999

Over the past couple of years, I've worked with Dale and Derrill Shuttleworth of Studio Two Ltd in Edmonton to prepare sketches and paintings related to tailings and closure landscape work. Their specialty is architectural renderings. The experience in working with these gentlemen has been an exceptional one – maybe some of the lessons would be less positive if not for the skill and experience of these artists.

Key lesson learned: Artist's renditions of proposed plans are a very useful and efficient tool for communicating with technical people as well as the public.

Lessons learned

1. A variety of plans and activities can be sketched or painted by an artist – a non-traditional method for communicating for most mining and geotechnical work.

2. Several items are needed for most sketches – a plan view (blueprint or plot), photographs of any key equipment or other facilities to be added, and photos of the region for vegetation. Inviting the artist to the site is a useful step in the process.

3. A simple grid system is drawn on the original map to create a perspective drawing. A rough draft of the final copy at full scale is created and this is reviewed with the client.

4. The process of creating these images is faster, cheaper, and produces better results than computerized / digitized work.

5. The Syncrude site is so large, that showing detail in this sweeping landscape is challenging. Some vertical exaggeration is necessary to show slopes and landforms.

6. Even engineers have difficulty in envisioning the results based on plan and cross-section drawings.

7. In making drawings from plans, there are numerous issues that come to light, a lot of decisions that have to be made – it turns out to be a useful process for working some of the details.

8. Some stakeholders will accuse one of "painting too good a picture" with artists' drawings. This may be true, but the paintings are more defendable if they are made as technically accurate as possible. Most of the imperfections are not visible at the scales of most paintings.

9. Getting the right artists is critical – it becomes part of a long-term relationship.

10. It terms of costs, hourly fees for artists are typically about half that of a very senior consulting civil or mining engineer. Simple sketches take an hour, vignette paintings about four to eight hours, a larger painting (2ft x 4ft) takes two to four days. The client needs to be providing direction for about half the time. Some of the work can be done by fax and over the phone, but the client time meeting with the artist is critical.

11. Copies are best made by getting a 4x5" photographic negative made of the original. Colour laser photocopies to 11x17" are also very useful, although the colours are distorted somewhat.

12. The artist can make five to ten 8x10" simple watercolour sketches in about a day – often enough to form and present the new ideas.

13. Simple ink sketches of ideas for tailings demonstrations (showing proposed equipment and deposits) can take as little as an hour, but provide a useful internal communication tool – much more so than plan view CAD drawings.

Supplement O

Lessons learned

Transalta's experience in certifying reclaimed lands at Highvale and Whitewood Mines

March 1998

A meeting was held with Transalta's Brent Hartley and Cam Bateman on March 10, 1998 to discuss their successful reclamation certification program. They have certified five blocks of land including an end-pit lake which has been turned back to the Alberta government. Following are the lessons learned from Transalta's experience.

Key lesson learned: Transalta has made certification routine and there is much that Syncrude can learn from their experience. As Syncrude is considering bringing its first piece of land — the S4 area — to the government for reclamation certification, the knowledge gained from Transalta's experience is extremely valuable and timely.

Lessons learned

1. Transalta considers progressive certification an important part of their sustainable development goals. Certification is their measure of successfully reclaiming land to a pre-agreed state. To date, they have certified five blocks of land — two were certified in the 1980s and one was certified in each of the past three years. Transalta's goal is to certify 100 hectares each year, about the same as their rate of disturbance. This method also allows direct feedback into their existing reclamation practice.

2. Historically at Transalta, certification was not pursued. Instead, about $250,000 was spent each year monitoring and researching the performance of the reclaimed land. Now, the focus is on certification. The only monitoring and inventory completed is the minimum (and just in time) required to support the certification program.

3. The documentation for certification is arranged in a comprehensive document that contains all of the available information about the land being certified. Transalta includes every sample and analysis to ensure there is full disclosure and to avoid being accused of withholding anything. The organization of this document is done in-house. It takes one dedicated person about six months to complete the document and the final cost, including the supporting studies, totals about $250,000 each year.

4. The documentation for certification adheres to the Alberta guidelines for reclamation certification which is currently being revised ("A guide to the preparation of applications and reports for coal and oil sands operations," 1991, Chapter 12). The guidelines are short and extremely clear as to what is required. Syncrude needs to assemble together the relevant legislation and regulations.

5. It is Transalta's belief that, from the moment the reclamation certificate is issued, there is no further liability for the land and no need for any monitoring past the certification date. In fact, Transalta believes that the government assumes all liability for the land. The company had to educate and convince the government that certification is not coincident with returning the land and that returning the land can be done at a later date.

6. The amount of documentation required becomes less each year. Beware of the government asking for too much monitoring.

7. The most important date is the one on which the land was disturbed. This is the date that will govern exactly which regulations apply to that land.

8. To ensure all information is included, Transalta uses an internal checklist before submitting the application. The main areas to cover in the certification report are:
   - dates of disturbance and major events
   - topography and erosion potential
   - soils
   - vegetation
   - water resources
   - wildlife and fisheries
   - post-development land use.

9. The certification report contains the following supporting documentation.

- Pre-mining information: (biophysical inventory, includes soils productivity baselines, vegetation maps, groundwater.)
- Construction: (includes quality and quantity of reclamation material placed.
- Post-mining: (includes biophysical inventory – done once, just before application,

productivity monitoring – every year,
groundwater monitoring.

10. While the first certification for Transalta was difficult, the process has now become routine. After reviewing the application, the government must either issue a certificate or a reclamation order, there is no middle ground. It usually takes several months to get the certificate.

11. It is helpful to have a yearly report in place which describes the events that occurred at the site and exactly where they occurred (disturbance, mining, reclamation).

12. The wildlife habitat assessment is based on the HEP, U.S. Fish & Wildlife. The erosion assessment is based on the Universal Soil Loss Equation.

13. The East Pit Lake was originally crown land and Transalta agreed to return the area, at least in part, as a lake. It was mined in 1982, reclaimed in 1986, and studied extensively thereafter. Transalta applied for certification in October 1993 and received it in September 1994. In 1996, the land was accepted back as crown land but the government did not want to manage it. Instead, a local fish and game club took over and currently operates it under a 21-year lease. Transalta contributed to the facilities that presently allow it to be utilized as a passive day use area.

Supplement P

Lessons learned

Reclamation certification process

March 1998

The following is a summary of what has been learned during the past two years about the certification of reclaimed mined land. The learnings are based mostly on various discussions held regarding the proposed reclamation certification of Syncrude's S4 Area.

Key lesson learned: The process for certification of reclaimed land in Alberta is fairly simple and straightforward. For small sites, especially wellsites, it is routine. For large mining landforms, however, where the projection of future long-term behaviour is less certain, the existing process may one day prove to be inadequate. Syncrude's S4 Area seems ideally suited as a first certification exercise.

Lessons learned

1. Reclamation certification of small tracts of land (a few hectares in size) is routine in Alberta. Hundreds or thousands of sites have been certified. It can even by done by phone

2. A process for gaining reclamation certification for coal and oil sands mines, as set out in "A guide to the preparation of applications and reports for coal and oil sands operations," 1991, Chapter 12, seems relatively straightforward. Main areas of interest are dates of disturbance and revegetation, topography and erosion potential, soils, vegetation, water resources, wildlife and fisheries, and post-development land use.

3. Each year, Transalta certifies the same amount of land it disturbs as part of a commitment to sustainable development. That amount is the same as its coal mines west of Edmonton. By successfully certifying about 100 hectares per year in each of the past three years, they have made certification routine.

4. Certification of Syncrude land may be more involved than Transalta's for a number of reasons: Syncrude is all leased crown land. Some of Transalta's land was crown land but the majority is privately owned by Transalta; Syncrude is in the Green Zone whereas Transalta is in the White Zone; Syncrude will have a lot of commercial forest versus Transalta's farmland, and Syncrude has greater relief and more erodible materials.

5. The liability for the land (vegetation and surficial) reverts to the crown immediately upon certification. However, the lease holder may hold onto the land past certification – control of the land does not revert to the crown automatically in Alberta.

6. If contaminated sites legislation kicks in, liability for contaminated soils remains with the mine. Thus, for example, liability for groundwater plumes remains with the mine.

7. While future repairs to the land (to correct poor performance) are the government's liability, it is likely the company will be asked (but not compelled) to help with costs. Since the company must protect its corporate image, it would probably agree to avoid potential adverse media coverage.

8. The amount of monitoring that is required must be negotiated but generally ends up being a small component of the reclamation costs. Much of what is required is simply an assessment just prior to certification, although a preliminary assessment part way through the pre-certification period would be useful to identify early problems. Some periodic monitoring is also necessary.

9. The monitoring program needs to be carefully considered and designed to capture the required information without being too expensive and onerous. A short yearly report is an excellent vehicle for this information.

10. There are ongoing concerns about the ability of new soils to generate commercial forests beyond the 14-year monitoring period. Plans to extend this confidence are in place but need to be more formally set out.

11. It is extremely important to keep track of when each piece of land was first disturbed and revegetated. This information determines which regulations apply to each piece. Geographical information systems (GIS) are integral to keeping good records.

12. The reclaimed landscape must be in very good condition to receive reclamation certification although some small defects are acceptable.

13. Certification for natural areas takes a minimum of about two to three years for grasslands, five years for if trees are planted. And an undefined amount of time for wetlands or waterbodies. Commercial forest takes 14 years.

14. Landform grading is becoming the norm for the oil sands region mainly to encourage more diversity in the landscape.

15. Landform drainage is an important consideration and should not be left until after landform construction. Costs to retrofit the structure for drainage can add 10 to 20 percent to the original reclamation cost.

16. Regional drainage should be left as lakes, streams, wetlands and rivers rather than pits and ditches.

17. It is important to set each certification unit into the regional setting for certification. The regional setting includes topography, land use, hydrology, and animal habitat/corridors. The closure plan fulfils this requirement but, as more land becomes certified, it reduces the flexibility for reclamation of adjacent lands because of commitments made in previous certification processes. There is then in essence a 'shadow zone' around each certified block that starts to limit options on adjacent land.

18. Gullying on mining landforms is seen by AEP as a major impediment to certification. While the S4 Area has some gullying, future landforms will likely have more erodible substrates and larger watersheds and, therefore, more gullying. Work has begun to better design future structures. At the same time, more work with regulators is needed to come to a common understanding about the acceptability of any erosion. It is Syncrude's position that some gullying in unavoidable, occurs in nature, and may be desirable for biodiversity and landform evolution.

19. There is concern about the use of some species for reclamation. Syncrude and AEP may need to come to a formal understanding of what constitutes acceptable reclamation species. Currently, both Syncrude and AEP believe it is presently clear but they are not necessarily in agreement.

20. Certification of bison ranching area will be an interesting challenge.

21. Syncrude and AEP have entered a long-term relationship (100+ years) to create and certify reclaimed land. It will be important for both sides to foster this relationship. The relationship must be cognizant of changing staff, regulations and philosophy as well as the ability to react to observed performance in designing future landscapes. A long history of certification will be built up – steps must be taken to ensure that each certification block proceeds amiably and doesn't create barriers to future certification.

22. It is my personal opinion that a small amount of low-intensity perpetual maintenance will be required for Lease 17/22. Although Syncrude can create a very good landscape, it seems unlikely that it can create such a complex system that will continue to perform perfectly under the influence of extreme and unpredictable events without occasional maintenance such as armouring eroding areas, removing blockages from streams and small fix-ups after extreme events. This does not alleviate the necessity of designing and constructing a very good landscape. Syncrude and AEP need to understand more about the potential for maintenance.

23. The S4 Area has already provided an excellent opportunity to establish a good certification partnership and some precedent for future mining landform. Syncrude should continue on the certification path and plan for the certification of future areas. Syncrude and AEP need to work closely in this work and in mapping out future blocks for certification. While certifying land is not expensive, it must be realistically budgeted.

24. Syncrude should formalize the tasks for certification and assign them to a team that has members assigned to specific tasks. Long-term participation of members in these teams would make the certification process more effective.

25. There is still a need for a number of tools to be developed that will help to build mining landforms that act more predictably and reliably over the long-term. The S4 Area has the benefit of being reasonably straightforward to certify but future mining landforms and systems will be much more complex.

26. The whole goal of building mining landforms is to economically place the materials in a suitable configuration so they can be reclaimed and returned to the crown. The return process is dominated by reclamation certification so, right from the pre-feasibility stage, landforms need to be designed for this eventuality, instead of leaving certification thinking until the end.

Supplement Q

Lessons learned

Natural and artificial gullies in the oil sands region

June 1998

This is a summary of observations and lessons from a helicopter tour on June 19, 1998 of some natural gullies in the oil sand region. Various types of gullies were selected in advance from a regional aerial photograph, marked on a map, then visited over the course of a day, stopping for a half-hour at each of five sites. The ideas presented here are based on our discussions.[19]

Key lesson learned: The natural landscape shows a wide range of physical stability. Gullies in the natural areas show a similarly wide range of behaviour. Gullies show threshold response – they erode little and produce little sediment most of the time, but change during extreme events. Self-healing mechanisms reduce the effects of extreme events and allow rapid healing after the event. Gullies on reclaimed landscapes should ideally be built in and have a variety of self-healing mechanisms that will allow them to also get better with time. Gullies that form outside of intended areas are acceptable, provided they can be shown to either be stable, or working towards an acceptable end point. Prediction of future stability of active gullies in reclaimed areas is a challenge to which we must invest some energy.

Lessons learned

1. The landscape in our region is dynamic and shows a wide range of stability / instability due to large landslides and gullies along the MacKay and Steepbank rivers, to active gullies along these oversteepened valley walls, to small sediment producing gullies along the Athabasca escarpment, to a stable, fairly tight subtle drainage system hidden beneath the trees on most slopes. Trees hide subtle topographic changes. It would be worthwhile to revisit these sites, do some transects and digging to better develop them as natural analogs.

2. Gullies tend to have a lot of vegetation in them, and there is a perpetual battle between the stabilizing power of vegetation (both as growing plants and as debris) and the erosive power of the water. For the most part, the vegetation wins, and the gullies are relatively stable.

3. Many of the gullies in the region are armoured with vegetation – characteristic of grassed waterways. During low flows, the water mostly seeps through the organic soil and woody vegetation in distributed channels across flat floodplains that are 10 to 30 metres wide, with slopes of 3 to 5 percent. During greater flows, shallow overland results, but the larger plants and the woody debris attenuate the energy. In most cases, rock does not seem to play a role in the morphology or performance of many of these channels.

4. Where channels are steeper and downcutting, rock clasts are more common. These range in size from gravel sized to boulders up to 1 to 2 metre in diameter. The steepest most channels produce a lot of sediment and have yet to form a good rock armour layer. These channels too are dominated by vegetation growing along the banks and lots of large woody debris in the channels. Design of self-armouring streams must ensure that the self-armouring occurs faster than the long-term erosion.

5. There is a subtle but real topography / drainage density in the shallow slopes along the Athabasca River and Clearwater River escarpments. The trees hide and stabilize these drainage systems. The microtopography is only visible by very subtle changes in vegetation type (and even then only occasionally), or when the area has been logged. It will be worthwhile to do some simple transects and map the drainage density in these areas and study the creek beds / swales better.

6. There is a lot of siltstone that is sound, hard, and performing well in the riverbeds and creek channels such as Stream R and the MacKay River.

7. During low flow, a lot of the stream flow is by shallow groundwater flow through the creekbeds.

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[19] This one-day field trip was organized by Syncrude, AEP and Golder Associates. Participants included Chris Hale and Chris Powter of AEP, Les Sawatsky of Golder, and Earl Anderson, Tom Coolen, and Gord McKenna of Syncrude. See also a detailed report of this tour.

8. The main concern with gullies on reclaimed ground is predicting their ultimate state. If they will get better with age, then they are probably okay. If they get worse with age, they are hard to certify. We need to determine the basis on which to determine if a landscape is too dynamic. What level of landscape maturity do we need to certify?

9. Geotechnical instability can lead to uncontrolled erosion and large gullies. This it is important to ensure geotechnical stability to control the formation and performance of gullies.

10. Trees stabilize the landscape by removing the water by evapotranspiration and thought their roots. As the trees grow, the landscape will become more and more stable. The trees also tend to hide gullies if they do form, and their roots stabilize the banks of the gullies and when the tree falls or drops branches, the large woody debris also helps to stabilize the gully (and add to the soil). So must slopes will tend to get better with time, particularly during the first few generations of trees. Arguing that the larger storms (like the 500-year storm) are likely farther off in the future, then there will likely be time for the forests to grow and stabilize the slopes. The slope should then be better prepared for extreme events and able to recover quickly.

11. Gullies show threshold responses. In times of low flow, self-healing mechanisms are fully active, the gullies are usually stable and producing little change and little sediment. During extreme events, the armouring is overwhelmed, and the gully erodes having exceeded some intrinsic threshold. During the event, *physical self-healing mechanisms* (such as bed lowering, rocks falling in from the banks, widening floodplain, levelling floodplain, and exposure of more armouring rock in the streambed, and debris accumulations) are active. As flows subside, *biological self-healing mechanisms* become active – grasses and brush move in, trees grow and mature, etc). Gullies then need to be stable below a reasonable threshold, should have physical and biological self-armouring mechanisms. With time, the channel becomes more and more stable, although the first extreme events may cause considerable change. These concepts are embodied in the idea of resilience, and being able to be flexible.

12. Tours such as this one between Syncrude and AEP regulators are very useful to help build common understanding of significant issues and provide a forum for good technical discussions abut pressing issues. It is important to keep focused on a single topic (such as gully hydrology). The tour today was very successful, and should be used to pattern future tours on an as-required basis.

Les Sawatsky's three main lessons from this trip:

- Natural terrain contains some active gullies but mainly mature swales and creeks
- Geomorphic vegetated waterways are capable of draining large areas (several square kilometres) and have a fairly steep slope.
- Natural areas on steep slopes (10 to 30 percent) have a swale density of about $5km/km^2$.

Supplement R

Lessons learned

Mine reclamation economics:
Choosing the amount and timing
of discretionary expenditures [20]

October 1998

The following lessons were learned in an investigation of the economics of reclamation and are based on a literature review, and discussions with economists and closure specialists.

Key lesson learned: There is no widely available method for determining the amount and timing of discretionary expenditures for mine reclamation. For most cases, the framework to use is Cost Benefit Analysis (CBA) with Discounted Cash Flows (DCF) (for lack of better tools) as one component of a decision.

Traditionally, benefits of reclamation are ignored in such analyses, resulting in the postponement of major costs, and minimizing discretionary costs. The analysis can be improved by attempting to estimate the stream of benefits, choosing separate discount rates for each cost and benefit, listing qualitative benefits separately, and recognizing that the CBA/DCF analysis is only one part of the decision.

Lessons learned

1. Here is a suggested approach for determining the amount and timing of discretionary expenditures for mine reclamation:

Step 1 – Decide on what the decision is attempting to optimize

Step 2 – Frame the problem or opportunity clearly and determine which factors are discretionary.

Step 3 – Create a reference case against which well-specified alternative cases will be compared.

Step 4 – Attempt to evaluate all costs and easily quantifiable benefits and their time profiles. List unquantifiable benefits separately.

Step 5 – Create a cash-flow model.

Step 6 – Carefully and transparently choose discount rates for each cost and benefit.

Step 7 – Construct a sensitivity analysis using real discount rates of zero percent (no discount), three percent (long-term risk-free), six percent (real commercial risk-free), and 10 percent (typical real commercial investment hurdle rate).

Step 8 – Report on all aspects of the findings including discussion of qualitative items.

Step 9 – Base decision on all available information using judgement.

Step 10 – Revisit decisions and analysis periodically to estimate goodness of decision, and learn better for next time.

2. The analysis is often very sensitive to the choice of discount rate, especially when long time periods are under consideration. Costs and benefits should be listed with no discounting for clarity. The following real (inflation-free) discount rates are suggested:

- Ten percent for reclamation projects where there is a risk of redisturbance or where new technologies are being implemented
- Six percent for projects where risks are near-zero (the work must be done). This is an estimate of the risk-free corporate time preference for money.
- Three percent for projects where benefits extend to the public and beyond the control of the mining company. This is one estimate of the social discount rate
- One percent for projects where burdensome costs that are transferred to future generations
- Zero percent and negative discount rates are not recommended. Use of these discount rates leads to illogical conclusions as described later.

3. In many cases, where there is the potential to delay large reclamation expenses without severely impacting benefits, it may be worthwhile to build a large demonstration using existing technology in the early days, and monitor and learn from it until near closure when the bulk of the cost will be incurred. This will help demonstrate to the public and the regulators that the mining company has the knowledge and expertise to accomplish the task. It will also provide an opportunity to learn from the demonstration over years or decades. For example, if 10 kilometres of permanent stream had to be re-established, one kilometre could be done as a demonstration and nine kilometres delayed until economically attractive.

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[20] From a report in preparation of the same title.

Supplement S

Lessons learned

Town closure planning

October 1998

Mine and town closures are difficult for most people to consider yet all resource towns have a limited lifespan. Town closure planning should be considered during all phases of a mine's and town's life. Mines and towns need to work together to ensure orderly development and closure. The following lessons learned are presented based on observations, research and interviews. Consideration for Fort McMurray and Syncrude is given.

Key lesson learned: Mines and towns need to work together throughout the course of their lives. Mines must be open and transparent about their labour needs and production life so the towns can plan accordingly.

Lessons learned

1. All mines have a finite life. Resource towns based on ongoing operation of mines in the area do not typically plan for closure.

2. Municipal planning is often carried out on the basis of one-year budgets. Occasionally only do longer-term plans exist and rarely do plans exist for more than five years.

3. Municipal planning is almost always done on the assumption of long-term growth, which is often fuelled by optimism about mining and mine development plans.

4. Town growth usually mirrors growth in development and operation of regional mines. The economic multiplier effect is a strong factor in town development. What is not generally recognized is that as a mine nears its life's end and production decreases in stages until it finally stops, there is a de-multiplier effect which has a great effect on the community. The value of real estate typically undergoes wide swings as a result in changes to employment in the region.

5. Miners and town planners are optimists at heart and there is seemingly little to be gained by being pessimistic, especially when trying to attract investors and development. This optimism pays little attention to ghost towns and other drastically downsized towns of yesteryear, perhaps willing to believe that their town is somehow different.

6. When mines eventually close, it usually comes slightly earlier than predicted and, although expected in the final years, hits the town hard. There is always mineralization left in the pit walls and there is often talk about recapitalization of the mine to extract the remaining riches and about future orebodies waiting to be discovered.

7. People often invest heavily in towns, through house and land purchase, and the development of small and medium sized businesses. These investments have very little value when a mine closes and may leave people bitter about their financial considerations. This bitterness is deepened by mixed messages being put out by the mines as they wind down. Towns often seek to stimulate other industries (farming, retirement communities, tourism, etc) in which activities are usually rather economically modest compared to mining.

8. Mine closures often go through a predictable transition. After operating for numerous years, profits start to dwindle and new partners, investment or other opportunities are sought, usually unsuccessfully. Maintenance levels and capital reinvestment levels start to decrease. A year or two before closure, about half the staff and most of the contractors are laid off (creating hard feelings in the town) and the remaining people work on extracting the remaining ore at higher and higher risks. Eventually one of the hazards occurs, and the mine shuts down a few months early. Staff is reduced temporarily to about 10 percent of its peak numbers and these employees process the last stockpiles and reclamation becomes the greatest single activity. Many mines shut down entirely within a month or two and remain largely unreclaimed while others continue reclamation activities for a year or two, reducing employees down to a handful.

9. Some towns are bulldozed flat when mining is finished but most have a few loyalists who stay. Town population levels are often about five to 10 percent of their peak. Facilities become more expensive to maintain and government assistance is sought. The municipality attempts to find new industries or investors but the remoteness of the community makes this difficult.

10. Sometimes at closure, citizens compel the mining company to pay a 'severance' fee to help the community through its transition. The first year or two after mine closure is a critical time for the

survival of the community. People are usually against the mine and one method of seeking retribution and employment is to complain about the state of reclamation.

11. Mines need to work more closely with community leaders and participate in joint planning sessions. Mines need to keep the community informed of their plans, especially as closure nears. Companies, in particular, need to avoid raising false expectations during the wind-down period.

12. Towns need to ensure that their mortgages and other commitments do not extend beyond conservative estimates of remaining mine life.

13. For short duration mines, the trend is to set up temporary camps or company towns so that when mining ends, there is no private ownership or long-term occupation of the land in the region. Where mines are expected to exist for longer periods, some consideration to building flexibility in municipal utilities is sometimes exercised. This allows for reductions in the quantity of utilities in stages as the town population declines.

14. Mines should work to attempt to reclaim as much as practical before closure so that the community cannot change expectations for the land which, in turn, can greatly increase the costs of reclamation.

15. Fort McMurray fits into the pattern of a resource town. The mines talk of operating for hundreds of years, real estate prices are closely tied with ramping up and down of employment, optimism is high and investment in the community is high. Expectations of a thriving but small community, even after oil sands mining, exist throughout the city. Regardless, McMurray is essentially a one-industry town and some consideration to long-term planning seems in order.

16. Mines and industries do not shut down only because of resource depletion. Fort McMurray has already seen a historic downturn due to a collapse of the fur industry. As is well known, the Stone Age did not end for lack of stone. Less workforce-intensive methods to extract the oil or a cheaper source of energy may be found one day.

17. Oil sands mining can be expected to occur well into the future in Fort McMurray. Signs of a downturn have yet to be seen and it is not clear what activities the city might engage in even if it did follow a closure plan. But the city should keep a weather eye to the day when oil sands mining goes into decline.

18. Mining companies in the oil sands may be open to lawsuits if they provide false signals. It is critical that the companies are open and conservative with their public communications and work closely with the community and its stakeholders.

Supplement T

Lessons Learned

B.C. Mine Reclamation Symposium 2000

November 2000

Each year, about 150 people, mostly reclamation specialists from around British Columbia, meet to share their recent experience and findings at this annual symposium. This year's tours and talks were excellent as always. The general mood of these people is upbeat despite prolonged low commodity prices and general stagnation of the mining industry in BC.

Key lesson learned:

Most BC mine land is being reclaimed to agricultural or wildlife grazing by use of agronomic grasses and legumes. Where shrub and trees are used, there is a focus on kicking off ecological succession using pioneer species.

Lessons learned

1. Mines will sometimes implement reclamation activities offsite such as creating fish habitat, a desert oasis, or open patches in the forest for wildlife foraging. There may be many reasons for this – it may show a broader approach to reclamation, a loss in focus, or a conscious decision that this expense is worthwhile as part of a public relations campaign, or perhaps mines feel forced into such arrangements as part of sweetening the pot during permitting.

2. Mines are now usually formally declaring a main land use for their reclamation design which is a new idea to most mines. The focus in B.C. is usually ranching or wildlife, but some sites are also targeting industrial and recreational uses.

3. Erosion controls (water and wind erosion) were mentioned frequently during talks at this symposium and control of erosion during construction remains a key issue. Areas with dispersive clays are particularly challenging as the solids are very slow to settle out in conventional settling ponds.

4. Many mines have very unique challenges and care must be taken to recognize this uniqueness in any all-encompassing approaches to mine reclamation.

5. Most B.C. mines have little or no organic matter for use in reclamation. The use of biosols is becoming widespread. Wastes from other industries are also under active investigation.

6. Governments are starting work on abandoned minesites but the efforts to date, while good, have only addressed a token number of sites. It seems that too much effort is going into surveys and design and not enough into just getting the job done. A crew with a dozer, backhoe, and truck can repair a large number of small sites quickly. Uncertainties over multi-year funding can limit options to single season construction seasons, which is sometimes non-optimal. A more pragmatic approach is needed.

7. Reclamation specialists do not usually have a good handle on unsaturated flow conditions. A good understanding is particularly important for covers on waste dumps and in designing soil profiles to support vegetation.

8. It is clear that hydrology of the soil is critical to good vegetation performance. At most sites, the soil geochemistry is also being recognized as a very important factor. Soil science seems to be secondary to vegetation and wildlife at B.C. mines.

9. Geographical information systems (GIS) are slowing coming to mine reclamation and are promising to be an important tool. Use of GIS with radio-collared animals is proving useful although expensive. If reclamation is to be truly integrated with operations, GIS systems must support both.

10. Little reclamation in B.C. is done with native plants. Those promoting native plants suggest the following preconditions for their use: good availability of native seed, comparable results to agronomics, and costs only minimally higher than agronomics.

11. Stakeholders are often interested in the options with the lowest risk. That could mean not necessarily the best option, the cheapest option or the option that provides the greatest benefit.

12. B.C. people generally accept the fact that most sites will require perpetual annual inspections and periodic maintenance.

13. There is a lot of work going into reclaiming for wildlife. Some of the work is token and some is short term, but quite a bit is very forward thinking in terms of being permanent and useful. Thinking is going into patch attribute design and adjacency.

14. Often reclamation research reaches the point where it has largely answered the key questions

and the technology is ready to either be shelved or go into production. Usually the researchers are the last to realize this point has been reached – researchers will always have unanswered questions. It is up to management and the researchers to clearly define the questions to be answered and critically review the results annually.

15. Mines starting since about 1995 are new generation mines and most begin with a modern closure plan. Their reclamation and reclamation research is more orderly and focused. Hopefully, they will encounter fewer problems, have reduced costs, fewer surprises and better landscape performance.

16. Filling of a mine pit at Gibraltar Mine with ARD surface water was much faster than calculated forcing the use of the tailings pond to store more water. The calculation error is attributed to neglecting or underestimating the groundwater flow into the pit. Mines almost never get pit filling right, and it is seldom conservative.

17. Island Copper has tremendous examples of productive end land uses – it uses seawater-filled mine pit for aquaculture (fish farming), its thickener tanks to raise sturgeon, other buildings for small businesses, and its nurse crop of 600,000 alders will be logged for pulp at a profit of $30 million.

18. Mine closure is a very difficult time for employees, the town, contractors, etc. It also takes a toll on those left behind. Post mining uses are important but employ only a tiny fraction of the number of people the mine used to employ. In fact, closing down a mine can be harder than starting one. There are suggestions in the academic literature that mines and governments should ensure no change in the socio-economic status of a mining community when a mine closes – clearly this is not possible for mining towns.

19. Main roosting and hibernating habitat for bats is now abandoned underground mines. As mines are sealed, critical habitat is being lost. Bat Conservation International has a special division that works with mines. Experiments with haul truck tire caves for open pit mines (on dump areas) is being piloted.

20. Island Copper had a technical environmental advisory board appointed by the federal and provincial governments that acted as an industry watchdog and advisory board, as well as overseeing monitoring. It has had some of the same members for over thirty years. This approach seems like a good one for mines, regulators and stakeholders.

21. A main goal of most reclamation is to reintroduce disturbed sites into the natural successional process. The initial vegetation cover should allow for invasion. Adopting this approach is technically sound and overcomes a lot of other problems with pseudo-climaxes and planting species mismatched to the ground.

22. Selenium is an important issue in mine spoils in some regions. Many areas are deficient in selenium and some areas have too much. Due to local adaptation and bioaccumulation issues, developing guidelines must be thoroughly done for site specific areas. Unfortunately, B.C. Ministry of the Environment is doing it unilaterally, using imported data, and being wildly conservative. Mines are banding together, trying to do it the right way. The ministry risks shutting down the mines without solving the problem.

23. Selenium is of particular concern for shallow end-pit lakes.

24. Dose response science is a lot more primitive, subjective, and political than one might suppose. One needs to get the original studies and raw data before drawing important conclusions.

Appendix B

Landscape performance risk assessment checklist

Table B-1 presents a list of failure modes, triggers, activities, and risks that can be used to develop a list of hazards and failure modes for a failure modes and effects analysis (FMEA).

Many of these items are mechanisms of natural landscape evolution and may not represent "failure" of the landscape (many may be considered beneficial change). A landform or landscape design should consider each of these, at least at a cursory level. It is recommended that the list be pre-screened, and that items in the resulting "short list" be rated according to likelihood and consequence and mitigated where necessary through design or maintenance. Residual risks can then be described.

It is important to note that the list is incomplete (it will likely never be complete) and that many of the failure modes will be linked spatially or temporally.

Use of this table has been successfully tested and proven useful for several landforms at the Syncrude Mildred Lake Operation, a large oil sands mine.

Table B-1 Hazards, triggers, activities and concerns for reclaimed landscapes.

Hazard, trigger, activity, or concern	Explanation
Physical	
Animal-induced erosion	Physically, animals can significantly affect the landscape in many ways. Perhaps the most common is beavers causing flooding and outburst flooding. Other examples include coral causing reefs, alligators causing wallows, bison causing wallows and trails, livestock causing trails, and mice, moles and voles causing burrowing.
Avulsion and flooding	Overtopping of stream channels by rivers at a high stage or due to blockage can cause flooding. Avulsion occurs where the floodwaters create a new channel and the old channel is abandoned or reduced in flow.
Bank erosion	Erosion of the sides of channels or streams by flowing water, typically along the outer bends of channels.
Blockage: Beaver dam	Blockage of a waterway by a beaver dam. Dams may be three to four metres and several hundred meters long. They can create or enlarge ponds to many square kilometres in size.
Blockage: Ice jam	Partial or complete blockage of a river or lake outlet by pieces of ice.
Blockage: Log jam	Partial or complete blockage of a river or lake outlet by a jumble of logs, sticks, and other woody debris.
Breaching	Loss of containment of a water or fluid tailings containment structure. Typically results in a large initial outburst flood followed by a much slower gradual or sporadic loss of contents. May be triggered by overtopping, piping, vandalism or sabotage, or a downstream or upstream failure.
Breakwater damage	Loss of rock and efficiency of a breakwater due to storm or earthquake loading.
Catastrophic outflow	Sudden flow of water, fluid or fluid tailings due to breaching, loss of blockage, or liquefaction of a slope.
Channel deposition	Deposition of material on channel floors or banks, often referred to as silting up but may be clay, sand or rock.
Creep (and solifluction)	Very slow downslope movement due to gravity and affected by solifluction, freeze-thaw, etc.
Debris flows	Very rapid flow of mud, rock, and vegetative debris along channels.
Deep-seated landslides	Downslope movement of materials along a weak plane or zone at depth.
Desiccation	Cracking of surface materials, particularly muds and clays, due to evaporation.
Drought	Prolonged periods with little or no rain.
Earthquake / tectonism	Natural shaking or trembling of the ground due to tectonic seismic or volcanic forces, or uplift or down-drop of blocks.
Explosion	Rapid expansive force due to rapid ignition of combustibles, particularly trapped methanogenic gas.
Fan deposition	Fan-shaped sediment deposit at an abrupt break in slope due to a reduced gradient of a stream or channel. Often an alluvial fan.

Hazard, trigger, activity, or concern	Explanation
Flowslide / liquefaction	Large, long-runout failure of slopes due to liquefaction of sediments (static or dynamic).
Fluctuating water levels	Unwanted changes in water levels in ponds and reservoirs
Glacial advance	Advance of local or continental ice sheet.
Gullies, headward erosion of	Water erosion of slopes forming ephemeral distinct narrow channels.
Ice mounds	Mounding of ice caused by retardation of artesian seepage pressures, typically 20 metres in diameter and 1.5 metres high.
Ice push	The lateral pressure exerted by the expansion or wind shear on shoreward moving ice, particularly on lakes and reservoirs.
Iceberg scour	Erosion of sea or lakebed by iceberg dragging
Icing	Freezing of channelized water forming deposits of ice that can fill a channel cross-section.
Infilling of water body	Heavy sedimentation or complete infilling of lakes or wetlands will cause the water depths to decrease.
Infiltration	The movement of surface water into soil or pervious rock.
Isostatic rebound	Rise of ground due to removal of overlying sediments or ice.
Lake overturning / mixing	The circulation, especially in fall and spring, of the layers of water in a lake or reservoir whereby surface water sinks and mixes with the bottom water. It is caused by changes in density differences due to changes in temperature and is especially common in lakes that are icebound in the winter.
Meteorite	Impact of a celestial body (comment, asteroid, meteorite) with a mine reclamation landscape.
Migrating dunes	Migrating wind deposits of sand or silt.
Overtopping	Water level of reservoir is greater than its containment.
Permafrost creation	Changes in substrates, vegetative cover, or microclimate which cause creation of permafrost.
Permafrost destruction	Changes in substrates , vegetative covers, fills, or microclimate which cause destruction of natural or artificial permafrost.
Piping	Increasing loss of sediment due to high groundwater gradients causing internal or tunnel erosion. Particularly problematic for tailings sand, silt, and dispersive clays.
Raindrop erosion	Erosion of material by raindrops due to direct impact or leaf drip.
Road construction	Construction of roads in reclaimed landscapes.
Road / trail deterioration	Deterioration of roads and trails through erosion, traffic or encroaching vegetation.
Sea level change	Change in relative sea level at shoreline.
Sheet erosion	Erosion of slopes by sheet flow. Also called slope wash.
Shoreline erosion	Erosion of shorelines by ice push, waves, long-shore currents.

Hazard, trigger, activity, or concern	Explanation
Silting up of wetlands/lakes	Infilling of wetlands, lakes, reservoirs due to sediments.
Slipoff failures	Shallow slope failures in top centimetres to few metres of substrates.
Slumps	The downward slipping of a mass of rock or unconsolidated material moving as a unit, usually with backward rotation on a more or less horizontal axis parallel to the cliff or slope form which it descents
Snow avalanche	A large mass of snow or ice falling, sliding or flowing very rapidly under the force of gravity, typically on a steep slope in alpine areas.
Spalling	Breakdown of a cliff or pitwall by exfoliation or weathering into fragments which fall down the slope and build up a rubble talus at the toe.
Spring sapping	Headward erosion of gullies due to concentration of seepage forces at the locus of the gully which accentuates erosion.
Stream avulsion	Change in stream course due to overtopping of channel banks.
Stream flooding	Flooding of land due to high stream water levels or downstream blockage. Catastrophic outflows from upstream (natural landslide or ice dams) or artificial dam breaks, beaver dam breaks, etc.).
Subsidence /consolidation	Settlement of fills due to densification or loss of material at depth.
Tsunami, surge, sieche, waves	Large ocean wave, or wave caused on a lake by a landslide running inshore (tsunami), or storm surge, or sieche (harmonic wave), or other extreme wave (monster wave).
Tunnel collapse	Some tunnels in rock or lined tunnels in soil left for permanent diversion of water may be susceptible to collapse or blockage.
Undermining	Collapse of surface features or facilities due to collapse into underground workings.
Vandalism or sabotage	Wilful degradation of landscape of facilities by others including staff, delinquents, or terrorists.
Volcanism	Deposition of lava or ash, landslides, sediment loading either from offsite or onsite.
War	Facilities may be threatened by war.
Wind erosion and deposition	Wind erosion of sand and silt particles (particularly tailings) and subsequent deposition in sheets or dunes.
Biological	
Blight / disease	A disease or injury of plants resulting in withering, cessation of growth and death of parts.
Blowdown / tornado	Loss or damage to vegetation due to storms or high winds.
Browsing	Grazing of plants and trees by wildlife.
Burial by sand	Partial or complete burial by wind-deposited sand or silt.
Climate change	Fluctuations in temperature, rainfall, snowfall, sunlight.
Cultivation	Working of soils for farming.
Dusting of leaves	Accumulation of fine wind-blown dust on leaves.

Hazard, trigger, activity, or concern	**Explanation**
Failure to set up nutrient cycle	Soils may fail to set up nutrient cycle in reasonably short time frames due to poor components or poor vegetation.
Fertilizing	Application of fertilization to reclaimed areas.
Fire: Forest	Forest wildfire.
Fire: Grass	Grass wildfire.
Fire: Muskeg / peat	Burning of thick deposits of muskeg or peat is relatively common if the soil is allowed to partially dry out. Spontaneous combustion (auto-ignition) is also relatively common.
Fire: Topsoil	Loss of very organic-rich topsoil due to wildfire.
Grazing	Use of land for grazing of domestic animals (sheep, cows, etc.)
Groundwater contaminating plants	Plant growth or viability affected by contaminated groundwater.
Groundwater contaminating animals	Animal health affected by contaminated groundwater.
Ice push	Thrusting of ice onto shore by expansion, wind or water currents on lakeshores or riverbanks.
Ice storm	Freezing rain causing icing (accumulation of ice) on vegetation and power lines.
Irrigation	Application of water to ground or plants to promote growth.
Logging	Removal of trees for lumber or pulp. Involves logging roads, trunk roads and sorting areas.
Loss of diversity	Over time, the landscape becomes less diverse, either through loss of species or age diversification in an area.
Micro-climate change	Changes to the climate by the construction of hills or lakes or the draining of large areas.
Non-native invasion offsite	Invasion of exotic plants from reclaimed area into adjacent natural area.
Non-native invasion onsite	Invasion of non-native plants from offsite (from nearby agricultural, forestry, or reclamation sites).
Not self-sustaining	Plants wither or die without ongoing human intervention.
Nutrient accumulation	Accumulation of nutrients causing excessive plant growth.
Over-fishing	Removal of too many fish of a certain species by fishing.
Over-hunting	Removal of too many animals of a certain species by hunting.
Over-grazing	Drastic reduction in vegetation through grazing pressure.
Over-trapping	Removal of too many animals of certain species by trapping.
Pseudo-climax	Planted reclamation species form stable community for decades or hundreds of years not allowing natural invasion of native species.
Salt accumulation / salt pan	Accumulation of salts in terrestrial areas through groundwater evaporation.
Salt fluctuations in water	Changes in salt concentrations in streams and wetlands over time.

Hazard, trigger, activity, or concern	Explanation
Vegetation undercut by gullies	Erosion leads to undercutting of trees and vegetation.
Unwanted succession	Replacement of desired plants by native invasion and natural succession.
Use of herbicides	Application of chemicals to control certain species.
Use of pesticides	Application of chemicals to control certain pest species.
Water table: Fluctuating	Water table fluctuates between too high and too low.
Water table: Too high	Water table is high enough to cause ground to be saturated, thereby affecting growth and rooting of plants.
Water table: Too low	Water table is too low for effective supply of moisture to plant roots.
Chemical	
Acid rock drainage (ARD)	Acid rock drainage is produced by the oxidation of sulphides exposed during mining, which produces sulphuric acid and sulphate salts. The acid dissolves minerals in the rocks, further degrading the quality of the drainage water.
Cementation	Precipitation of a mineral cement along the grains of the sediment.
Coal fire	Burning of in-situ coal seams or coal refuse. Coal fire is often due to spontaneous combustion but may be due to other sources of ignition.
Decementation	Leaching of precipitation of mineral cements in a granular material.
Gas evolution	Generation and release of gas from wastes or underground mines.
Leachates	Chemically contaminated groundwater from leaching of minerals in fills.
Piping in dispersive clays	Freshwater migration through sodic clays resulting in surface and tunnel erosion and, in the case of dam cores, potential failure.
Radioactivity	The property possessed by some elements (like uranium) of spontaneously emitting alpha, beta or, sometimes, gamma rays by the disintegration of the nuclei of atoms.
Spontaneous combustion	Self-ignition of combustible materials through chemical action (like oxidation) of its constituents.
Human health and safety	
Barrels and debris	Debris left in the reclaimed landscape after mining.
Bioaccumulation / food chain	Increase in toxicity up the food chain which ultimately presents hazards to humans at the end of the food chain.
Boreholes / wells	Cylindrical vertical voids left by drilling or well activity.
Breach / flooding	Loss of reservoir on stream contents causing danger to humans.
Cliffs	Vertical bluffs.
Deteriorating road	Unmaintained or poorly maintained mine road or access road may expose motorists to danger.
Dust	Wind-borne material from disturbed areas.
Dynamite / blasting caps	Explosives or detonators left behind after mining.
Fences	Fences, which are left behind as part of the landscape, can cause accidents by

Hazard, trigger, activity, or concern	Explanation
	people running into them.
Fog	Fog may be created by artificial water bodies and may present hazards to motorists or planes in adjacent areas. Fog may also freeze to roadways or bridges causing slippery conditions.
Gas	Poisonous gases of lack of oxygen in confined spaces
Groundwater contamination	Potential of human ingestion of contaminated groundwater.
Highwall ravelling / falls	Rock falls from steep pit walls.
Ingestion	Consumption of contaminated soils.
Old bridges	Decaying bridge collapsing under load.
Old buildings	Old and decaying mining buildings.
Old equipment	Decaying old equipment.
Pits and water bodies	Danger to people drowning in old pits or water bodies.
Power lines / substations	Live electrical lines left over after mining or used for ongoing landscape maintenance. This may cause problems for other lines which are down, planes, tall equipment, or children playing in the area.
Quicksand	A soft, shifting semi-liquid that yields easily to pressure and can suck down and swallow heavy objects that touch its surface. This highly mobile mass is formed by saturated loose silt or sand with upward flowing water.
Radioactivity	Exposure of people or animals to unacceptably high levels of radioactivity or radon.
Rapids / falls	Rapids or falls created on artificial waterways.
Shafts / portals	Exposed or poorly capped shafts present hazards to people traversing the land or exploring caves.
Silicosis	Damage to lungs by fine particles of silica.
Sinkholes	A circular hole in the ground caused by exposure of underground voids left by dissolution, piping, or undermining.
Slides / flowslides	Landslides and flowslides.
Soft shoreline on lakes	Soft shorelines on lakes making access hazardous.
Thin ice	Hazardously thin ice cover on rivers or lakes.
Untrafficability	People, who are hiking or driving vehicles, get stuck in untrafficable land.
Uneven ground	Varying microtopography.
Wildlife or insect attack	Attack by wildlife or insects on reclaimed land.
Failure to perform intended function	
Act as aquifer	Some substrates may be designed to transmit water.
Aesthetics	Landscape is not aesthetically pleasing to public – based on visual, olfactory, or other criteria.
Affect water temperatures	Some bodies of water are designed to mitigate water temperature.

Hazard, trigger, activity, or concern	Explanation
Avoid sterilizing ore	There is often a design intent to sterilize as little ore as practical.
Barrier: Sight	A strip of trees or a long berm designed to limit visual access from roadways or rivers.
Barrier: Sound	A solid fence or windrow that blocks direct sound transmission, usually to residential areas.
Contain / isolate fluids	Reservoirs and dams contain fluids.
Contain / isolate solids	Containment or isolation of solids – usually covered dumps and pits.
Corridor: Industrial	Landforms may be designed to provide corridors for a variety of uses.
Corridor: Road	
Corridor: Wildlife	
Corridor: Transportation	
Corridor: Wildlife	
End land use	Landscapes are usually designed to permit certain land uses.
Firewall	Some landscape elements may be designed to resist transmitting of failure modes – for example rocky areas to minimize risk of spread of wildlife, armouring of lake outlets to prevent downcutting and downstream damage.
Foundation soils	Areas may be designed to provide suitable foundations for buildings, roads, or other facilities.
Groundwater barrier	Fills or slurry walls may be designed to reduce fluxes of groundwater.
Littoral zone	Shallow areas of lakes may be designed to provide productive littoral zones
Meet corporate objectives	There may be mining company landscape performance objectives or agreements to meet.
Meet design or code	There may be specific design elements or codes to meet
Regulate water discharge	The discharge of water to the environment may be regulated with a dam or weir.
Regulatory: Receive regulatory approval	A landform or landscape will be designed to meet regulatory approval. It may also be designed to meet expected future regulatory conditions.
Regulatory: Continue to meet future regulatory approval	
Support infrastructure	Landscape may be designed to support mine operations, maintenance or other infrastructure.
Support vegetation	Most landscapes are designed to promote vegetation and there may be agreements for certain productivity levels.
Trafficable	Landscape is usually designed to provide trafficability to people, animals, and certain equipment.
Trap sediments	Some areas of the landscape may be designed to improve water quality by trapping sediment.
Water: Attenuate	Lakes and wetlands may be designed to attenuate water flows.

Hazard, trigger, activity, or concern	Explanation
Water: Gather	Some hydrologic elements (lakes, wetlands, creeks) are designed to gather water usually for release via a river or pipe.
Water: Release	Elements designed to release surface water to the receiving environment.
Water: Store	Some elements, such as lakes and wetlands, are designed to store water.
Water: Transmit	Rivers and creeks are designed to transmit water safely.
Water: Cleaning/ treatment	Active (water treatment plants) and passive (wetlands and lakes) may be designed to improve water quality.
Waves: Attenuate / block	Some elements, such as breakwaters, may be designed to attenuate or block waves.

Appendix C

Database of Syncrude oil sand tailings sand hydraulic conductivity measurements

Abbreviation	Name	Description
	Sample types	
IV	In-situ – vertical	Insitu permeability, measured in vertical direction
IH	In-situ - horizontal	In-situ permeability, measured in horizontal direction
RN	Remoulded – natural	Remoulded tailings sand at natural (as-received) fines content.
FPV	Fixed piston sample – vertical	Sample collected using a fixed piston sampler and tested in the lab in a vertical direction.
FPH	Fixed piston sample – horizontal	Sample collected using a fixed piston sampler and tested in the lab in a horizontal direction.
FH	Frozen – horizontal	Naturally frozen tailings sand, sampled, mounted, thawed, and tested in a horizontal direction
FV	Frozen – vertical	Naturally frozen tailings sand, sampled, mounted, thawed, and tested in a vertical direction
	Test types	
CA	Calculated - assumed	Values chosen for design purposes by skilled professionals
CB	Calculated – back analyzed	Values determined through back-analysis of seepage through two-dimensional cross-sections
FC	Field – constant head standpipe permeability test	Field standpipe permeability test using a constant head.
FD	Field - drainage	Field test measuring drainage towards a ditch or pipe
FF	Field – falling head standpipe permeability test	Field standpipe falling head standpipe permeability (slug) test.
FG	Field – gradient test	Measurement of gradient and flux between standpipes or standpipes and filter drains.
FI	Field - infiltration	Measurement of field infiltration using single-ring, double ring, or Guelph permeameters.
FP	Field – percolation test	Rapid, coffee-can (single ring) percolation tests
FQ	Field – cone dissipation test	Dissipation of excess pressures generated during cone penetration test (CPT)
FU	Field – pump test	Shallow pump test.
FS	Field - consolidation	Dissipation of tailings sand in vertical direction due to consolidation after loading with a fresh lift
L	Laboratory – undifferentiated test	Laboratory permeability test – method and direction undifferentiated (mostly remoulded permeameter tests)
LF	Lab – falling head permeameter test	Falling head permeability test in the lab
LH	Lab – constant head laboratory test	Constant head permeability test in the lab
LM	Lab – model test	Laboratory model dam test

Sample / test information							Measured				Assumed for design			
#	Program	Year	Borehole number	Sample type	Test type	Scale volume m^3	k_h cm/s	k_v cm/s	k_u cm/s	k_h/k_v	k_h cm/s	k_v cm/s	k_u cm/s	k_h/k_v
G-001	MLSB Design	1977		None	CA	6.78E+06					1.60E-04	1.00E-05		16
G-002	MLSB Design	1977		None	CA	6.78E+06					1.00E-03	1.00E-03		1
G-003	MLSB Filters	1983		None	CA	6.78E+06					1.60E-04	1.00E-05		16
G-004	MLSB Filters	1983		None	CA	6.78E+06					1.00E-03	1.00E-03		1
G-005	MLSB Design	1990		None	CB	6.78E+06	2.00E-04	1.25E-05		16				
G-006	SWSS Design	1991		None	CA	4.36E+06					2.00E-03	1.25E-04		16
G-007	Infiltration 1996	1996		IV	FI	2.50E-02		1.00E-03						
G-008	Infiltration 1996	1996		IV	FI	2.50E-02		8.80E-05						
G-009	Infiltration 1996	1996		IV	FI	2.50E-02		1.87E-04						
G-010	Infiltration 1996	1996		IV	FI	2.50E-02		1.04E-03						
G-011	Infiltration 1996	1996		IV	FI	2.50E-02		5.09E-04						
G-012	Infiltration 1996	1996		IV	FI	2.50E-02		3.92E-05						
G-013	Infiltration 1996	1996		IV	FI	2.50E-02		7.50E-05						
G-014	Infiltration 1996	1996		IV	FI	2.50E-02		1.75E-04						
G-015	Infiltration 1996	1996		IV	FI	2.50E-02		2.63E-05						
G-016	Suncor Infiltration 1995	1996		IV	FI	2.50E-02		3.94E-03						
G-017	Suncor Infiltration 1995	1996		IV	FI	2.50E-02		4.59E-03						
G-018	Suncor Infiltration 1995	1996		IV	FI	2.50E-02		4.63E-03						
G-019	Suncor Infiltration 1995	1996		IV	FI	2.50E-02		3.99E-03						
G-020	Suncor Infiltration 1995	1996		IV	FI	2.50E-02		3.04E-03						
G-021	Suncor Infiltration 1995	1996		IV	FI	2.50E-02		3.17E-03						
G-022	Suncor Infiltration 1995	1996		IV	FI	2.50E-02		5.86E-04						
G-023	Suncor Infiltration 1995	1996		IV	FI	2.50E-02		1.50E-03						
G-024	Suncor Rainfall	1996		IV	FI	2.50E-02		1.99E-03						

Sample / test information							Measured				Assumed for design			
#	Program	Year	Borehole number	Sample type	Test type	Scale volume m^3	k_h cm/s	k_v cm/s	k_u cm/s	k_h/k_v	k_h cm/s	k_v cm/s	k_u cm/s	k_h/k_v
	Erosion 95													
G-025	Suncor Rainfall Erosion 95	1996		IV	FI	2.50E-02		1.13E-03						
G-026	Suncor Rainfall Erosion 95	1996		IV	FI	2.50E-02		6.14E-04						
G-027	Suncor Rainfall Erosion 95	1996		IV	FI	2.50E-02		1.71E-03						
G-028	Suncor Rainfall Erosion 95	1996		IV	FI	2.50E-02		4.05E-03						
G-029	Suncor Rainfall Erosion 95	1996		IV	FI	2.50E-02		6.25E-03						
G-030	Syncrude Rainfall Erosion 95	1996		IV	FI	2.50E-02		7.62E-04						
G-031	Syncrude Rainfall Erosion 95	1996		IV	FI	2.50E-02		2.33E-04						
G-032	Syncrude Rainfall Erosion 95	1996		IV	FI	2.50E-02		7.09E-04						
G-033	Syncrude Rainfall Erosion 95	1996		IV	FI	2.50E-02		8.50E-04						
G-034	Syncrude Rainfall Erosion 95	1996		IV	FI	2.50E-02								
G-035	Syncrude SWSS Standpipes 96	1996	SP9651G-03	IH	FF	2.00E-02	6.00E-03							
G-036	Syncrude SWSS Standpipes 96	1996	SP9631N-11	IH	FF	2.00E-02	1.03E-03							
G-037	Syncrude SWSS Standpipes 96	1996	SP9651N-05	IH	FC	2.00E-02	1.02E-03							
G-038	Syncrude SWSS Standpipes 96	1996	SP9631N-11	IH	FC	2.00E-02	7.00E-04							
G-039	Syncrude SWSS Standpipes 96	1996	SP9651N-05	IH	FC	2.00E-02	7.00E-04							
G-040	Syncrude SWSS Standpipes 96	1996	SP9631N-11	IH	FC	2.00E-02	5.20E-04							
G-041	Syncrude SWSS Standpipes 96	1996	SP9651N-05	IH	FF	2.00E-02	5.20E-04							

Sample / test information							Measured				Assumed for design			
#	Program	Year	Borehole number	Sample type	Test type	Scale volume m^3	k_h cm/s	k_v cm/s	k_u cm/s	k_h/k_v	k_h cm/s	k_v cm/s	k_u cm/s	k_h/k_v
G-042	Syncrude SWSS Standpipes 96	1996	SP9551N-07	IH	FF	2.00E-02	5.00E-04							
G-043	Syncrude SWSS Standpipes 96	1996	SP9631G-12	IH	FC	2.00E-02	4.20E-04							
G-044	Syncrude SWSS Standpipes 96	1996	SP9631G-12	IH	FC	2.00E-02	4.10E-04							
G-045	Syncrude SWSS Standpipes 96	1996	SP9550N-17	IH	FF	2.00E-02	4.00E-04							
G-046	Syncrude SWSS Standpipes 96	1996	S[9531N-06	IH	FF	2.00E-02	2.30E-04							
G-047	Syncrude SWSS Standpipes 96	1996	SP9631N-11	IH	FF	2.00E-02	2.30E-04							
G-048	Syncrude SWSS Standpipes 96	1996	SP9551N-02	IH	FF	2.00E-02	1.80E-04							
G-049	Syncrude SWSS Standpipes 96	1996	SP9531N-08	IH	FF	2.00E-02	1.80E-04							
G-050	Syncrude SWSS Standpipes 96	1996	SP9551N-06	IH	FF	2.00E-02	1.50E-04							
G-051	Syncrude SWSS Standpipes 96	1996	SP9631N-10	IH	FF	2.00E-02	1.50E-04							
G-052	Syncrude SWSS Standpipes 96	1996	SP9631N-11	IH	FF	2.00E-02	1.50E-04							
G-053	Syncrude SWSS Standpipes 96	1996	SP9651N-04	IH	FF	2.00E-02	1.40E-04							
G-054	Syncrude SWSS Standpipes 96	1996	SP9531N-07	IH	FF	2.00E-02	1.30E-04							
G-055	Syncrude SWSS Standpipes 96	1996	SP9550N-16	IH	FF	2.00E-02	1.10E-04							
G-056	Syncrude SWSS Standpipes 96	1996	SP9631G-12	IH	FF	2.00E-02	1.10E-04							
G-057	Syncrude SWSS Standpipes 96	1996	SP9531N-05	IH	FF	2.00E-02	1.10E-04							
G-058	Syncrude SWSS Standpipes 96	1996	SP9631G-12	IH	FF	2.00E-02	1.00E-04							
G-059	Syncrude SWSS Standpipes 96	1996	SP9631N-11	IH	FF	2.00E-02	9.00E-05							

Sample / test information							Measured				Assumed for design			
#	Program	Year	Borehole number	Sample type	Test type	Scale volume m^3	k_h cm/s	k_v cm/s	k_u cm/s	k_h/k_v	k_h cm/s	k_v cm/s	k_u cm/s	k_h/k_v
G-060	Syncrude SWSS Standpipes 96	1996	SP9551N-05	IH	FF	2.00E-02	4.00E-05							
G-061	Syncrude SWSS Standpipes 96	1996	SP9550N-15	IH	FF	2.00E-02	4.00E-05							
G-062	Syncrude SWSS Standpipes 96	1996	SP9651N-01	IH	FF	2.00E-02	3.80E-05							
G-063	SWSS Landscape Design 96	1997		Upper bound	CA	4.36E+06					8.00E-04	5.00E-05		16
G-064	SWSS Landscape Design 96	1997		Lower bound	CA	4.36E+06					1.00E-04	6.25E-06		16
G-065	MLSB Paper	1986		None	CB	6.78E+06	1.00E-03	1.00E-04		10				
G-066	Seepage paper	1979		None	CB	6.78E+06	1.00E-04	1.00E-05		10				
G-067	Seepage paper	1979		None	CB	6.78E+06	1.00E-03	1.00E-03		1				
G-068	Seepage Analysis	1980		None	CA	6.78E+06					1.60E-04	1.00E-05		16
G-069	Spiking 1995 Cone Dissipation	1995	GE BH9534C-26	None	FQ	1.00E-04	1.43E-06							
G-070	Spiking 1995 Cone Dissipation	1995	GE BH9534C-27	None	FQ	1.00E-04	1.82E-06							
G-071	Spiking 1995 Cone Dissipation	1995	GE BH9534C-27	None	FQ	1.00E-04	6.64E-06							
G-072	Spiking 1995 Cone Dissipation	1995	GE BH9534C-27	None	FQ	1.00E-04	1.07E-07							
G-073	Spiking 1995 Cone Dissipation	1995	GE BH9534C-27	None	FQ	1.00E-04	5.53E-08							
G-074	Spiking 1995 Cone Dissipation	1995	GE BH9534C-27	None	FQ	1.00E-04	6.63E-08							
G-075	Spiking 1995 Cone Dissipation	1995	GE BH9534C-34	None	FQ	1.00E-04	2.52E-06							
G-076	Spiking 1995 Cone Dissipation	1995	GE BH9548C-07	None	FQ	1.00E-04	9.44E-06							
G-077	Spiking 1995 Cone Dissipation	1995	GE BH9548C-07	None	FQ	1.00E-04	2.72E-06							
G-078	Spiking 1995 Cone Dissipation	1995	GE BH9548C-08	None	FQ	1.00E-04	1.19E-05							
G-079	Spiking 1995 Cone	1995	GE BH9548C-08	None	FQ	1.00E-04	2.66E-06							

Sample / test information							Measured				Assumed for design			
#	Program	Year	Borehole number	Sample type	Test type	Scale volume m^3	k_h cm/s	k_v cm/s	k_u cm/s	k_h/k_v	k_h cm/s	k_v cm/s	k_u cm/s	k_h/k_v
	Dissipation													
G-080	Spiking 1995 Cone Dissipation	1995	GE BH9548C-10	None	FQ	1.00E-04	8.81E-07							
G-081	Spiking 1995 Cone Dissipation	1995	GE BH9548C-11	None	FQ	1.00E-04	5.58E-06							
G-082	Spiking 1995 Cone Dissipation	1995	GE BH9548C-11	None	FQ	1.00E-04	1.72E-06							
G-083	Spiking 1995 Cone Dissipation	1995	GE BH9548C-11	None	FQ	1.00E-04	1.11E-06							
G-084	Seepage SWSS 1996	1996	Steve Tan	None	CA	4.36E+06					8.00E-04	5.00E-05		16
G-085	Spiked tailings 1993	1993	Steve Tan	None	FF	2.00E-02	1.60E-05	1.00E-06		16				
G-086	Peter Byrne	1995	Steve Tan	None	CA	7.74E-04							1.56E-03	
G-087	1994 MFT Spiking	1995	TP-1N Cell 34	RN	LH	7.74E-04			1.70E-04					
G-088	1994 MFT Spiking	1995	TP-1N Cell 34	RN	LH	7.74E-04			1.70E-04					
G-089	1994 MFT Spiking	1995	Cell 33-1 East Pit	RN	LH	7.74E-04			2.00E-04					
G-090	1994 MFT Spiking	1995	Cell 33-1 East Pit	RN	LH	7.74E-04			6.00E-04					
G-091	1994 MFT Spiking	1995	Cell 33-3	RN	LH	7.74E-04			2.00E-04					
G-092	1994 MFT Spiking	1995	Cell 33-3	RN	LH	7.74E-04			7.00E-06					
G-093	1994 MFT Spiking	1995	BH9534T-37	FPV	LH	7.74E-04		1.50E-04						
G-094	1994 MFT Spiking	1995	BH9534T-37	FPV	LH	7.74E-04		2.00E-04						
G-095	1994 MFT Spiking	1995	BH9534T-42	FPV	LH	7.74E-04		4.00E-05						
G-096	1994 MFT Spiking	1995	BH9534T-43	FPV	LH	7.74E-04		7.50E-05						
G-097	1994 MFT Spiking	1995	BH9509T-01	FPV	LH	7.74E-04		1.50E-04						
G-098	1994 MFT Spiking	1995	BH9510T-01	FPV	LH	7.74E-04		5.00E-04						
G-099	Sand Sludge 1995	1995		RN	LF	7.74E-04			2.63E-04					
G-100	Sand Sludge 1995	1996		RN	LF	7.74E-04			2.18E-04					
G-150	Toe Berm Application	1990		None	CA	5.00E+05					1.60E-03	1.00E-04		16
G-151	Toe berm design	1990		None	CB	5.00E+05	2.00E-03	1.25E-04		16				
G-152	Toe berm design	1992		None	CA	5.00E+05					7.00E-03	4.38E-04		16

Sample / test information							Measured				Assumed for design			
#	Program	Year	Borehole number	Sample type	Test type	Scale volume m^3	k_h cm/s	k_v cm/s	k_u cm/s	k_h/k_v	k_h cm/s	k_v cm/s	k_u cm/s	k_h/k_v
G-153	Syncrude in-pit berm	1992		None	CB	2.50E+06	2.00E-03	1.25E-04		16	1.00E-03	1.00E-04		10
G-154	Syncrude in-pit berm	1986	Cell	None	CA	2.50E+06					4.00E-03	1.00E-03		4
G-155	Syncrude in-pit berm	1986	Beach	None	CA	2.50E+06					4.00E-03	4.00E-03		1
G-156	Syncrude in-pit berm	1986	Cell toe (graded)	None	CA	2.50E+06					2.00E-03	1.25E-04		16
G-157	Syncrude in-pit berm	1991		None	CA	2.50E+06								
G-158	Syncrude toe berm	1990		None	CB	5.00E+05	2.00E-03	1.25E-04		16				
G-159	MLSB Design	1999		None	CA	6.78E+06					8.00E-04	5.00E-05		16
G-160	Tailings technical design number 1999	1993		None	FC	6.78E+06	1.60E-05							
G-161	Spiking 1993 Cell 9 (1995 Spiking Report)	1993	BH9510T-01	RN	L	7.74E-04		4.80E-04						
G-162	Hardy 1986	1986		RN	L	7.74E-04			7.5E-06					
G-163	Hardy 1986	1986		RN	L	7.74E-04			4.5E-04					
G-164	Hardy 1986	1986		RN	L	7.74E-04			4.0E-03					
G-165	Morgenstern 77	1977		RN	L	7.74E-04			3.0E-07					
G-166	Morgenstern 77	1977		RN	L	7.74E-04			4.0E-07					
G-167	Morgenstern 77	1977		RN	L	7.74E-04			1.5E-06					
G-168	Morgenstern 77	1977		RN	L	7.74E-04			7.0E-06					
G-169	Pollock 88	1988		RN	L	7.74E-04			2.0E-06					
G-170	SCL 93	1993		RN	L	7.74E-04			6.0E-08					
G-171	SCL 93	1993		RN	L	7.74E-04			1.0E-07					
G-172	SCL 93	1993		RN	L	7.74E-04			2.9E-07					
G-173	SCL 93	1993		RN	L	7.74E-04			3.0E-07					
G-174	SCL 93	1993		RN	L	7.74E-04			3.6E-07					
G-175	SCL 93	1993		RN	L	7.74E-04			6.0E-07					
G-176	Syncrude seepage	1994		None	CA	6.78E+06					8.00E-04	5.00E-05		16

Sample / test information							Measured				Assumed for design			
#	Program	Year	Borehole number	Sample type	Test type	Scale volume m^3	k_h cm/s	k_v cm/s	k_u cm/s	k_h/k_v	k_h cm/s	k_v cm/s	k_u cm/s	k_h/k_v
	analysis													
G-177	SWSS Seepage Study	1996	Upper bound	None	CA	6.78E+06					8.00E-04	8.89E-05		9
G-178	SWSS Seepage Study	1996	Lower bound	None	CA	6.78E+06					8.00E-04	5.00E-05		16
G-179	SWSS Seepage Study	1996	Upper bound	None	CA	6.78E+06					1.00E-04	1.11E-05		9
G-180	SWSS Seepage Study	1996		None	CA	6.78E+06					1.00E-04	6.25E-06		16
G-181	SWSS Seepage Study	1996		None	FI	6.78E+06		1.70E-04						
G-182	Suncor TID 1977	1977	Lower bound	None	CA	4.50E+05	1.00E-03							
G-183	Suncor TID 1977	1977	Upper bound	None	CA	4.50E+05	1.00E-03							
G-184	Suncor TID 1977	1977	Lower bound	None	CA	4.50E+05	1.00E-04							
G-185	Suncor TID 1977	1977	Upper bound	None	CA	4.50E+05	5.00E-05							
G-186	Suncor TID 1977	1977	Lower bound	None	CA	4.50E+05	3.00E-05							
G-187	Suncor TID 1977	1977	Lower bound	None	CA	4.50E+05	1.00E-03							
G-188	Suncor TID 1977	1977	Upper bound	None	CA	4.50E+05	1.00E-04							
G-189	Suncor TID 1977	1977	Lower bound	None	CA	4.50E+05	1.00E-05							
G-190	Suncor TID 1977	1977		None	L	8.00E-03		8.00E-06						
G-191	Suncor TID 1977	1977		None	CA	4.50E+05	2.00E-02	5.00E-03		4				
G-192	Suncor TID 1977	1977		None	CA	4.50E+05					5.00E-04	5.56E-05		9
G-193	Suncor TID 1977	1977		None	CA	4.50E+05					2.00E-03	6.67E-04		3
G-194	Suncor TID 1977	1977	Lower bound	None	L	8.00E-03		2.00E-05						
G-195	Suncor TID 1977	1977	Upper bound	None	L	8.00E-03		2.00E-04						
G-196	Suncor TID 1977	1977		None	L	8.00E-03		8.00E-06						
G-197	Suncor TID 1977	1977		None	CB	4.50E+05		7.00E-05						
G-198	Suncor TID 1977	1977		None	CB	4.50E+05		1.20E-05						
G-199	Oslo Spiking	1991		None	FF	7.74E-04	5.00E-04							
G-200	Oslo Spiking	1991		None	FF	7.74E-04	3.50E-05							

Sample / test information							Measured				Assumed for design			
#	Program	Year	Borehole number	Sample type	Test type	Scale volume m^3	k_h cm/s	k_v cm/s	k_u cm/s	k_h/k_v	k_h cm/s	k_v cm/s	k_u cm/s	k_h/k_v
G-201	Oslo Spiking	1991		None	FF	7.74E-04	1.80E-04							
G-202	Oslo Spiking	1991		None	FF	7.74E-04	1.50E-04							
G-203	Oslo Spiking	1991		None	FF	7.74E-04	3.40E-05							
G-204	Oslo Spiking	1991		None	FF	7.74E-04	1.80E-04							
G-205	Oslo Spiking	1991		None	FF	7.74E-04	9.00E-04							
G-206	Oslo Spiking	1991		None	FF	7.74E-04	4.50E-04							
G-207	Oslo Spiking	1991		None	FF	7.74E-04	1.00E-03							
G-208	SWSS Buried Channel Aquifer	1990		None	CA	6.78E+06							2.00E-05	16
G-209	Starter dyke, Cell 11+12 toe berm	1990		None	CA	5.00E+05					2.00E-04	1.25E-05		16
G-210	Starter dyke, Cell 11+12 toe berm	1990		None	CA	5.00E+05					2.00E-03	1.25E-04		16
G-211	Starter dyke, Cell 11+12 toe berm	1990		None	CA	5.00E+05					2.00E-04	5.00E-05		4
G-212	Starter dyke, Cell 11+12 toe berm	1990		None	CA	5.00E+05					2.00E-03	5.00E-04		4
G-213	Starter dyke, Cell 11+12 toe berm	1990		None	CA	5.00E+05					2.00E-04	5.00E-05		4
G-214	Starter dyke, Cell 11+12 toe berm	1990		None	CA	5.00E+05					2.00E-03	5.00E-04		4
G-215	Starter dyke, Cell 11+12 toe berm	1990		None	CA	5.00E+05					2.00E-04	2.00E-04		1
G-216	Starter dyke, Cell 11+12 toe berm	1990		None	CA	5.00E+05					2.00E-03	2.00E-03		1
G-217	Seepage control risk assessment	1986		None	CA	5.00E+05					1.60E-04	1.00E-05		16
G-218	Seepage control risk assessment	1986		None	CA	5.00E+05							1.00E-03	
G-219	Seepage Section 53660mN	1980		None	CA	5.00E+05					1.60E-04	1.00E-05		16
G-220	Alsands	1980		None	CA	5.00E+05								16
G-221	Alsands	1980		None	CA	5.00E+05								4

Sample / test information							Measured				Assumed for design			
#	Program	Year	Borehole number	Sample type	Test type	Scale volume m^3	k_h cm/s	k_v cm/s	k_u cm/s	k_h/k_v	k_h cm/s	k_v cm/s	k_u cm/s	k_h/k_v
G-222	OSLO Design	1991		None	CA	5.00E+05					2.00E-03	1.20E-04		16.7
G-223	SWSS Lysimeter	1999	Test 1	None	FI	5.00E-03			2.07E-03					
G-224	SWSS Lysimeter	1999	Test 2	None	FI	5.00E-03			1.36E-03					
G-225	SWSS Lysimeter	1999	Test 3	None	FI	5.00E-03			6.53E-04					
G-226	Mildred Lake East TB Design	1997		None	CA	6.78E+06					2.00E-03	1.20E-04		16.7
G-227	Gradient measurements	2000	SP98-11-02 to PN91-11-14	None	FG	1.49E+04	8.95E-05							
G-228	Gradient measurements	2000	PN90-08-03 to SP90-08-04	None	FG	3.42E+03	1.13E-04							
G-229	Gradient measurements	2000	SP91-11-06 to SP-94-11-01	None	FG	2.56E+03	1.50E-04							
G-230	Gradient measurements	2000	PN90-08-03 to PN86-08-03	None	FG	1.49E+04	1.56E-04							
G-231	Gradient measurements	2000	PN91-11-14 to SP91-11-06	None	FG	1.13E+04	1.75E-04							
G-232	Gradient measurements	2000	PN86-04-05 to PN91-04-04	None	FG	1.08E+03	2.07E-04							
G-233	Gradient measurements	2000	SP90-08-04 to PN86-08-03	None	FG	2.41E+03	2.29E-04							
G-234	Gradient measurements	2000	PN85-09-02 to PN85-09-03	None	FG	7.43E+03	2.48E-04							
G-235	Gradient measurements	2000	PN86-04-05 to PN91-04-04	None	FG	1.59E+03	2.53E-04							
G-236	Gradient measurements	2000	SP98-17-02 to PN91-17-07	None	FG	5.17E+02	2.72E-04							
G-237	Gradient measurements	2000	SP98-08-01 to PN86-08-03	None	FG	1.08E+05	2.99E-04							
G-238	Gradient measurements	2000	B-02 Filter to SP90-04-23	None	FG	3.93E+04	3.13E-04							
G-239	Gradient measurements	2000	SP98-11-02 to SP-94-11-01	None	FG	7.48E+04	3.19E-04							
G-240	Gradient measurements	2000	SP98-08-01 to SP90-08-04	None	FG	1.23E+05	3.22E-04							
G-241	Gradient	2000	SP99-01-01 to	None	FG	2.74E+03	3.39E-04							

Sample / test information							Measured				Assumed for design			
#	Program	Year	Borehole number	Sample type	Test type	Scale volume m^3	k_h cm/s	k_v cm/s	k_u cm/s	k_h/k_v	k_h cm/s	k_v cm/s	k_u cm/s	k_h/k_v
G-241	Gradient measurements	2000	SP99-01-01 to PN86-01-01	None	FG	2.74E+03	3.39E-04							
G-242	Gradient measurements	2000	PN85-06-01 to PN87-06-05	None	FG	1.12E+04	3.64E-04							
G-243	Gradient measurements	2000	SP98-11-02 to SP91-11-06	None	FG	4.64E+04	3.73E-04							
G-244	Gradient measurements	2000	PN91-11-14 to SP-94-11-01	None	FG	1.40E+04	4.42E-04							
G-245	Gradient measurements	2000	PN88-06-54 to PN87-06-05	None	FG	1.34E+04	4.68E-04							
G-246	Gradient measurements	2000	PN85-10-02 to PN85-10-04	None	FG	1.70E+03	4.70E-04							
G-247	Gradient measurements	2000	PN91-12-08 to SP91-12-02	None	FG	2.10E+04	5.02E-04							
G-248	Gradient measurements	2000	PN91-04-05 to PN91-04-04	None	FG	2.27E+05	5.33E-04							
G-249	Gradient measurements	2000	SP98-08-01 to PN90-08-03	None	FG	6.50E+04	5.63E-04							
G-250	Gradient measurements	2000	PN91-04-05 to PN91-04-04	None	FG	1.77E+05	5.82E-04							
G-251	Gradient measurements	2000	PN88-06-54 to PN85-06-01	None	FG	2.59E+04	5.84E-04							
G-252	Gradient measurements	2000	PN91-04-05 to PN86-04-05	None	FG	1.53E+05	6.36E-04							
G-253	Gradient measurements	2000	PN86-04-05 to B-02 Filter	None	FG	9.46E+04	6.66E-04							
G-254	Gradient measurements	2000	SP98-04-01 to PN91-04-04	None	FG	2.55E+05	6.70E-04							
G-255	Gradient measurements	2000	PN91-04-05 to B-02 Filter	None	FG	4.08E+05	6.98E-04							
G-256	Gradient measurements	2000	PN91-04-05 to PN86-04-05	None	FG	9.40E+04	7.74E-04							
G-257	Gradient measurements	2000	PN85-18-15 to B14-FILTER	None	FG	3.57E+04	7.86E-04							
G-258	Gradient measurements	2000	SP98-04-01 to B-02 Filter	None	FG	2.16E+05	8.08E-04							

Sample / test information							Measured				Assumed for design			
#	Program	Year	Borehole number	Sample type	Test type	Scale volume m^3	k_h cm/s	k_v cm/s	k_u cm/s	k_h/k_v	k_h cm/s	k_v cm/s	k_u cm/s	k_h/k_v
G-259	Gradient measurements	2000	PN85-05-01 to PN85-05-02	None	FG	2.33E+03	9.12E-04							
G-260	Gradient measurements	2000	PN91-04-04 to B-02 Filter	None	FG	5.27E+04	9.15E-04							
G-261	Gradient measurements	2000	SP98-04-01 to PN86-04-05	None	FG	1.05E+05	9.20E-04							
G-262	Gradient measurements	2000	PN86-18-01 to PN85-18-04	None	FG	5.87E+03	9.40E-04							
G-263	Gradient measurements	2000	SP90-04-22 to SP90-04-08	None	FG	8.77E+03	9.51E-04							
G-264	Gradient measurements	2000	PN86-18-01 to B14-FILTER	None	FG	4.96E+05	9.53E-04							
G-265	Gradient measurements	2000	PN85-18-04 to B14-FILTER	None	FG	2.48E+05	9.57E-04							
G-266	Gradient measurements	2000	SP98-18-02 to B14-FILTER	None	FG	4.69E+05	1.11E-03							
G-267	Gradient measurements	2000	SP98-06-01 to PN88-06-54	None	FG	2.12E+05	1.26E-03							
G-268	Gradient measurements	2000	SP98-11-04 to SP98-11-05	None	FG	2.35E+05	1.31E-03							
G-269	Gradient measurements	2000	SP98-06-01 to PN87-06-05	None	FG	7.73E+05	1.43E-03							
G-270	Gradient measurements	2000	PN86-18-01 to PN85-18-15	None	FG	3.42E+04	1.45E-03							
G-271	Gradient measurements	2000	SP98-18-02 to PN85-18-04	None	FG	2.44E+04	1.80E-03							
G-272	Gradient measurements	2000	SP98-18-02 to PN86-18-01	None	FG	1.88E+03	2.19E-03							
G-273	Gradient measurements	2000	B-02 Filter to PN86-04-07	None	FG	2.89E+04	2.25E-03							
G-274	Gradient measurements	2000	SP98-18-02 to PN85-18-15	None	FG	1.05E+04	2.29E-03							
G-275	Gradient measurements	2000	SP98-06-01 to PN85-06-01	None	FG	1.09E+05	2.62E-03							
G-276	Gradient measurements	2000	SP90-04-22 to SP90-04-08	None	FG	3.75E+03	3.05E-03							

Sample / test information							Measured				Assumed for design			
#	Program	Year	Borehole number	Sample type	Test type	Scale volume m^3	k_h cm/s	k_v cm/s	k_u cm/s	k_h/k_v	k_h cm/s	k_v cm/s	k_u cm/s	k_h/k_v
G-277	Gradient measurements	2000	PN81-19-10 to SP83-19-04	None	FG	1.90E+04	4.89E-03							
G-278	Gradient measurements	2000	PN85-18-04 to PN85-18-15	None	FG	7.37E+03	5.07E-03							
G-279	Gradient measurements	2000	PN85-10-04 to B-21 FILTER	None	FG	1.44E+02	1.02E-05							
G-280	Gradient measurements	2000	B21-FILTER to SP98-11-04	None	FG	6.07E+04	1.47E-04							
G-281	Gradient measurements	2000	PN90-08-03 to B21-FILTER	None	FG	3.65E+04	1.63E-04							
G-282	Gradient measurements	2000	PN86-08-03 to B21-FILTER	None	FG	3.66E+03	1.78E-04							
G-283	Gradient measurements	2000	SP90-08-04 to B21-FILTER	None	FG	1.27E+04	2.01E-04							
G-284	Gradient measurements	2000	SP91-11-06 to B21-FILTER	None	FG	1.32E+04	2.13E-04							
G-285	Gradient measurements	2000	PN85-09-03 to B-22 FILTER	None	FG	3.00E+03	2.35E-04							
G-286	Gradient measurements	2000	PN85-09-02 to B-22 FILTER	None	FG	1.28E+04	2.42E-04							
G-287	Gradient measurements	2000	PN91-17-07 to B-16 FILTER	None	FG	1.41E+05	2.48E-04							
G-288	Gradient measurements	2000	B-22 FILTER to PN85-05-03	None	FG	1.11E+04	2.51E-04							
G-289	Gradient measurements	2000	SP90-20-03 to B13-FILTER	None	FG	7.72E+03	2.60E-04							
G-290	Gradient measurements	2000	SP98-08-01 to B21-FILTER	None	FG	2.15E+05	2.71E-04							
G-291	Gradient measurements	2000	SP-94-11-01 to B21-FILTER	None	FG	6.37E+03	2.72E-04							
G-292	Gradient measurements	2000	SP98-17-02 to B-16 FILTER	None	FG	1.02E+05	2.91E-04							
G-293	Gradient measurements	2000	PN85-10-02 to B-21 FILTER	None	FG	1.39E+04	2.99E-04							
G-294	Gradient measurements	2000	PN85-05-02 to B-22 FILTER	None	FG	4.03E+03	3.12E-04							

Sample / test information							Measured				Assumed for design			
#	Program	Year	Borehole number	Sample type	Test type	Scale volume m^3	k_h cm/s	k_v cm/s	k_u cm/s	k_h/k_v	k_h cm/s	k_v cm/s	k_u cm/s	k_h/k_v
G-295	Gradient measurements	2000	SP98-11-02 to B21-FILTER	None	FG	8.20E+04	3.32E-04							
G-296	Gradient measurements	2000	B21-FILTER to SP83-08-05	None	FG	7.37E+03	3.44E-04							
G-297	Gradient measurements	2000	PN85-09-04 to B-22 FILTER	None	FG	8.74E+02	3.45E-04							
G-298	Gradient measurements	2000	PN85-07-02 to B-21 FILTER	None	FG	2.09E+03	4.22E-04							
G-299	Gradient measurements	2000	SP93-03-02 to PN90-03-01	None	FG	8.05E+01	4.68E-04							
G-300	Gradient measurements	2000	PN85-06-01 to B-22 FILTER	None	FG	1.97E+04	4.74E-04							
G-301	Gradient measurements	2000	B21-FILTER to SP98-11-05	None	FG	3.02E+05	4.81E-04							
G-302	Gradient measurements	2000	PN91-03-05 to PN90-03-01	None	FG	3.38E+04	4.85E-04							
G-303	Gradient measurements	2000	PN88-06-54 to B-22 FILTER	None	FG	5.98E+04	5.20E-04							
G-304	Gradient measurements	2000	PN86-04-05 to B-02 FILTER	None	FG	5.61E+04	5.52E-04							
G-305	Gradient measurements	2000	SP96-16-01 to SP96-16-06	None	FG	3.76E+03	5.54E-04							
G-306	Gradient measurements	2000	SP98-16-10 to SP91-16-09	None	FG	3.95E+04	5.85E-04							
G-307	Gradient measurements	2000	SP98-16-10 to SP96-16-07	None	FG	3.82E+04	6.05E-04							
G-308	Gradient measurements	2000	SP98-16-10 to B17-FILTER	None	FG	1.28E+05	6.36E-04							
G-309	Gradient measurements	2000	SP96-16-01 to B17 FILTER	None	FG	6.22E+03	6.37E-04							
G-310	Gradient measurements	2000	PN85-05-01 to B-22 FILTER	None	FG	9.72E+03	6.67E-04							
G-311	Gradient measurements	2000	PN91-03-05 to B-02 FILTER	None	FG	4.17E+05	6.71E-04							
G-312	Gradient measurements	2000	PN91-04-05 to B-02 FILTER	None	FG	4.06E+05	6.93E-04							

Sample / test information							Measured				Assumed for design			
#	Program	Year	Borehole number	Sample type	Test type	Scale volume m^3	k_h cm/s	k_v cm/s	k_u cm/s	k_h/k_v	k_h cm/s	k_v cm/s	k_u cm/s	k_h/k_v
G-313	Gradient measurements	2000	PN91-12-08 to B-17 FILTER	None	FG	9.13E+04	7.03E-04							
G-314	Gradient measurements	2000	PN88-20-03 to PN90-20-06	None	FG	7.12E+03	7.11E-04							
G-315	Gradient measurements	2000	PN91-04-04 to B-02 FILTER	None	FG	2.13E+04	7.30E-04							
G-316	Gradient measurements	2000	PN88-18-16 to PN84-18-05	None	FG	1.27E+04	7.82E-04							
G-317	Gradient measurements	2000	PN88-18-16 to B-14 FILTER	None	FG	1.05E+05	8.06E-04							
G-318	Gradient measurements	2000	SP91-16-09 to SP96-16-07	None	FG	3.79E+03	8.31E-04							
G-319	Gradient measurements	2000	SP98-17-02 to PN91-17-01	None	FG	1.41E+03	8.53E-04							
G-320	Gradient measurements	2000	SP91-12-02 to B-17 FILTER	None	FG	3.48E+04	8.79E-04							
G-321	Gradient measurements	2000	SP93-03-02 to B-02 FILTER	None	FG	3.34E+04	8.97E-04							
G-322	Gradient measurements	2000	PN87-06-05 to B-22 FILTER	None	FG	1.59E+03	9.63E-04							
G-323	Gradient measurements	2000	SP91-16-09 to B17-FILTER	None	FG	3.44E+03	9.95E-04							
G-324	Gradient measurements	2000	PN90-03-01 to B-02 FILTER	None	FG	1.00E+05	9.98E-04							
G-325	Gradient measurements	2000	SP96-16-06 to B17 FILTER	None	FG	1.31E+03	1.17E-03							
G-326	Gradient measurements	2000	SP98-06-01 to B-22 FILTER	None	FG	5.86E+05	1.38E-03							
G-327	Gradient measurements	2000	b-02 FILTER to SP90-04-22	None	FG	2.98E+05	1.41E-03							
G-328	Gradient measurements	2000	PN83-03-03 to PN83-03-02	None	FG	3.70E+03	1.42E-03							
G-329	Gradient measurements	2000	SP96-16-07 to B17-FILTER	None	FG	1.65E+03	1.42E-03							
G-330	Gradient measurements	2000	PN84-18-05 to B-14 FILTER	None	FG	2.23E+03	1.99E-03							

Sample / test information							Measured				Assumed for design			
#	Program	Year	Borehole number	Sample type	Test type	Scale volume m^3	k_h cm/s	k_v cm/s	k_u cm/s	k_h/k_v	k_h cm/s	k_v cm/s	k_u cm/s	k_h/k_v
G-331	Gradient measurements	2000	PN91-11-14 to B21-FILTER	None	FG	1.14E+04	2.55E-03							
G-332	Gradient measurements	2000	PN91-17-01 to SP98-17-03	None	FG	2.96E+06	3.55E-03							
G-333	Gradient measurements	2000	SP98-17-02 to SP98-17-03	None	FG	2.73E+06	4.39E-03							
G-334	Gradient measurements	2000	PN83-03-03 to SP94-03-01	None	FG	6.70E+03	5.37E-03							
G-335	Gradient measurements	2000	SP98-04-01 to PN91-04-05	None	FG	9.34E+03	8.07E-03							
G-336	Gradient measurements	2000	B-21 FILTER to SP91-07-03	None	FG	2.35E+05	1.49E-02							
G-337	Gradient measurements	2000	PN81-19-10 to B14-FILTER	None	FG	2.78E+05	1.58E-02							
G-338	Gradient measurements	2000	SP90-07-09 to SP91-07-03	None	FG	4.61E+04	1.68E-02							
G-339	Gradient measurements	2000	SP83-19-04 to B14-FILTER	None	FG	1.33E+05	6.58E-02							
G-340	Gradient measurements	2000	B-21 FILTER to SP90-07-09	None	FG	3.17E+04	1.46E-01							
G-341	Gradient measurements	2000	SP81-03-04 to SP81-03-01	None	FG	8.41E+02	2.67E-05							
G-342	Gradient measurements	2000	SP99-28-01 to PN83-28-04	None	FG	1.92E+04	2.78E-05							
G-343	Gradient measurements	2000	PN86-27-01 to PN86-27-02	None	FG	1.05E+03	2.91E-05							
G-344	Gradient measurements	2000	SP99-28-01 to PN83-28-03	None	FG	6.16E+04	3.08E-05							
G-345	Gradient measurements	2000	SP99-28-01 to SP83-28-01	None	FG	8.98E+04	4.27E-05							
G-346	Gradient measurements	2000	PN83-28-04 to PN83-28-03	None	FG	1.64E+03	4.75E-05							
G-347	Gradient measurements	2000	SP94-02-01 to PN93-02-01	None	FG	4.00E+01	4.79E-05							
G-348	Gradient measurements	2000	B-22 FILTER to PN85-06-03	None	FG	3.58E+02	5.21E-05							

Sample / test information							Measured				Assumed for design			
#	Program	Year	Borehole number	Sample type	Test type	Scale volume m^3	k_h cm/s	k_v cm/s	k_u cm/s	k_h/k_v	k_h cm/s	k_v cm/s	k_u cm/s	k_h/k_v
G-349	Gradient measurements	2000	SP94-27-01 to SP81-27-15	None	FG	6.62E+03	6.26E-05							
G-350	Gradient measurements	2000	PN86-27-01 to SP81-27-15	None	FG	5.50E+04	8.34E-05							
G-351	Gradient measurements	2000	PN86-27-02 to SP94-27-01	None	FG	4.03E+03	9.69E-05							
G-352	Gradient measurements	2000	PN90-20-06 to B-13 FILTER	None	FG	3.41E+02	1.22E-04							
G-353	Gradient measurements	2000	SP99-21-02 to SP90-21-03	None	FG	1.60E+04	1.22E-04							
G-354	Gradient measurements	2000	PN86-27-02 to SP81-27-15	None	FG	2.06E+04	1.31E-04							
G-355	Gradient measurements	2000	PN83-28-04 to SP83-28-01	None	FG	1.85E+04	1.31E-04							
G-356	Gradient measurements	2000	SP99-21-02 to SP90-21-02	None	FG	4.26E+04	1.33E-04							
G-357	Gradient measurements	2000	PN86-27-01 to SP94-27-01	None	FG	9.78E+03	1.51E-04							
G-358	Gradient measurements	2000	SP90-21-03 to SP90-21-02	None	FG	9.30E+03	1.53E-04							
G-359	Gradient measurements	2000	SP99-21-02 to B-12 FILTER	None	FG	6.56E+04	1.59E-04							
G-360	Gradient measurements	2000	PN83-03-02 to SP94-03-01	None	FG	3.24E+01	2.10E-04							
G-361	Gradient measurements	2000	SP90-21-03 to B-12 FILTER	None	FG	1.20E+04	2.15E-04							
G-362	Gradient measurements	2000	PN87-24-09 to PN85-24-01	None	FG	2.69E+01	2.54E-04							
G-363	Gradient measurements	2000	SP94-02-01 to SP94-02-02	None	FG	8.44E+03	3.69E-04							
G-364	Gradient measurements	2000	SP99-01-01 to PN86-01-03	None	FG	1.78E+04	3.79E-04							
G-365	Gradient measurements	2000	B-22 FILTER to SP90-06-04	None	FG	1.78E+04	3.81E-04							
G-366	Gradient measurements	2000	PN86-02-01 to PN93-02-01	None	FG	6.52E+03	3.88E-04							

Sample / test information							Measured				Assumed for design			
#	Program	Year	Borehole number	Sample type	Test type	Scale volume m^3	k_h cm/s	k_v cm/s	k_u cm/s	k_h/k_v	k_h cm/s	k_v cm/s	k_u cm/s	k_h/k_v
G-367	Gradient measurements	2000	SP94-03-01 to SP81-03-03	None	FG	7.38E+03	3.90E-04							
G-368	Gradient measurements	2000	SP99-01-01 to SP94-01-01	None	FG	3.49E+04	3.98E-04							
G-369	Gradient measurements	2000	PN86-01-01 to PN86-01-03	None	FG	9.29E+03	3.99E-04							
G-370	Gradient measurements	2000	PN86-01-01 to SP94-01-01	None	FG	2.29E+04	4.16E-04							
G-371	Gradient measurements	2000	PN86-20-03 to B13-FILTER	None	FG	1.94E+04	4.30E-04							
G-372	Gradient measurements	2000	PN86-01-03 to SP94-01-01	None	FG	3.04E+03	4.41E-04							
G-373	Gradient measurements	2000	PN88-20-03 to B-13 FILTER	None	FG	9.01E+03	4.41E-04							
G-374	Gradient measurements	2000	PN83-03-02 to SP81-03-03	None	FG	5.14E+03	4.51E-04							
G-375	Gradient measurements	2000	PN86-24-01 to PN85-24-09	None	FG	6.97E+03	4.54E-04							
G-376	Gradient measurements	2000	PN86-02-01 to SP94-02-02	None	FG	2.87E+04	4.97E-04							
G-377	Gradient measurements	2000	SP99-02-01 to PN93-02-01	None	FG	3.16E+04	4.98E-04							
G-378	Gradient measurements	2000	PN86-24-02 to PN84-24-03	None	FG	3.33E+04	4.99E-04							
G-379	Gradient measurements	2000	PN86-24-02 to PN85-24-09	None	FG	1.18E+04	5.05E-04							
G-380	Gradient measurements	2000	SP99-02-01 to SP94-02-02	None	FG	1.94E+04	5.57E-04							
G-381	Gradient measurements	2000	PN86-24-02 to PN86-24-01	None	FG	1.62E+04	5.61E-04							
G-382	Gradient measurements	2000	PN86-24-01 to PN84-24-03	None	FG	3.11E+04	5.68E-04							
G-383	Gradient measurements	2000	PN86-24-02 to B-12 FILTER	None	FG	1.12E+05	5.68E-04							
G-384	Gradient measurements	2000	PN83-03-03 to SP81-03-03	None	FG	5.72E+04	5.72E-04							

Sample / test information							Measured				Assumed for design			
#	Program	Year	Borehole number	Sample type	Test type	Scale volume m^3	k_h cm/s	k_v cm/s	k_u cm/s	k_h/k_v	k_h cm/s	k_v cm/s	k_u cm/s	k_h/k_v
G-385	Gradient measurements	2000	SP99-23-01 to PN86-23-09	None	FG	1.99E+04	5.86E-04							
G-386	Gradient measurements	2000	PN91-25-01 to PN86-25-01	None	FG	4.35E+03	5.93E-04							
G-387	Gradient measurements	2000	SP90-21-02 to B-12 FILTER	None	FG	5.57E+03	6.13E-04							
G-388	Gradient measurements	2000	PN85-24-09 to PN84-24-03	None	FG	1.68E+04	6.15E-04							
G-389	Gradient measurements	2000	SP99-25-01 to PN86-25-01	None	FG	2.84E+04	6.17E-04							
G-390	Gradient measurements	2000	PN91-25-01 to B12-FILTER	None	FG	5.12E+04	6.25E-04							
G-391	Gradient measurements	2000	SP99-25-01 to B12-FILTER	None	FG	8.79E+04	6.37E-04							
G-392	Gradient measurements	2000	PN86-25-01 to B12-FILTER	None	FG	1.58E+04	6.68E-04							
G-393	Gradient measurements	2000	PN86-24-01 to B-12 FILTER	None	FG	7.61E+04	7.04E-04							
G-394	Gradient measurements	2000	PN86-02-01 to SP94-02-01	None	FG	1.82E+04	7.07E-04							
G-395	Gradient measurements	2000	PN87-24-09 to B-12 FILTER	None	FG	3.70E+04	7.12E-04							
G-396	Gradient measurements	2000	SP99-02-01 to SP94-02-01	None	FG	4.80E+04	7.13E-04							
G-397	Gradient measurements	2000	SP99-21-01 to sp91-29-01	None	FG	2.01E+05	7.17E-04							
G-398	Gradient measurements	2000	SP99-02-01 to PN86-02-01	None	FG	7.76E+03	7.19E-04							
G-399	Gradient measurements	2000	SP99-20-04 to B-13 FILTER	None	FG	2.30E+04	7.39E-04							
G-400	Gradient measurements	2000	PN85-24-01 to B-12 FILTER	None	FG	1.86E+04	7.80E-04							
G-401	Gradient measurements	2000	PN93-02-01 to SP94-02-02	None	FG	2.57E+03	7.97E-04							
G-402	Gradient measurements	2000	PN86-20-03 to SP90-20-03	None	FG	3.22E+03	8.01E-04							

Sample / test information							Measured				Assumed for design			
#	Program	Year	Borehole number	Sample type	Test type	Scale volume m^3	k_h cm/s	k_v cm/s	k_u cm/s	k_h/k_v	k_h cm/s	k_v cm/s	k_u cm/s	k_h/k_v
G-403	Gradient measurements	2000	SP99-25-01 to PN91-25-01	None	FG	4.21E+02	8.36E-04							
G-404	Gradient measurements	2000	SP99-20-04 to PN88-20-03	None	FG	1.11E+04	8.52E-04							
G-405	Gradient measurements	2000	PN87-24-08 to B-12 FILTER	None	FG	1.16E+05	8.64E-04							
G-406	Gradient measurements	2000	PN85-24-09 to B-12 FILTER	None	FG	2.55E+04	8.73E-04							
G-407	Gradient measurements	2000	PN85-23-07 to B12-FILTER	None	FG	9.43E+03	9.16E-04							
G-408	Gradient measurements	2000	SP99-23-01 to B12-FILTER	None	FG	1.64E+05	9.22E-04							
G-409	Gradient measurements	2000	SP99-23-01 to PN85-23-07	None	FG	1.50E+05	9.24E-04							
G-410	Gradient measurements	2000	SP99-23-01 to PN-85-23-11	None	FG	2.19E+05	9.64E-04							
G-411	Gradient measurements	2000	PN87-24-08 to PN85-24-01	None	FG	1.20E+04	1.00E-03							
G-412	Gradient measurements	2000	PN86-23-09 to B12-FILTER	None	FG	1.14E+05	1.17E-03							
G-413	Gradient measurements	2000	PN85-23-07 to PN-85-23-11	None	FG	4.34E+03	1.20E-03							
G-414	Gradient measurements	2000	PN87-24-08 to PN87-24-09	None	FG	8.80E+03	1.24E-03							
G-415	Gradient measurements	2000	PN86-23-09 to PN-85-23-11	None	FG	1.55E+05	1.28E-03							
G-416	Gradient measurements	2000	PN86-23-09 to PN85-23-07	None	FG	7.66E+04	1.31E-03							
G-417	Gradient measurements	2000	PN83-28-03 to SP83-28-01	None	FG	1.05E+04	1.40E-03							
G-418	Gradient measurements	2000	SP99-20-04 to PN90-20-06	None	FG	4.21E+04	1.54E-03							
G-419	Gradient measurements	2000	PN84-24-03 to B-12 FILTER	None	FG	4.12E+03	2.63E-03							
G-420	Gradient measurements	2000	PN92-28-01 to PN83-29-01	None	FG	2.57E+04	2.79E-03							

Sample / test information							Measured				Assumed for design			
#	Program	Year	Borehole number	Sample type	Test type	Scale volume m^3	k_h cm/s	k_v cm/s	k_u cm/s	k_h/k_v	k_h cm/s	k_v cm/s	k_u cm/s	k_h/k_v
G-421	Gradient measurements	2000	SP99-19-02 to PN81-19-10	None	FG	4.33E+04	3.05E-03							
G-422	Gradient measurements	2000	SP99-19-02 to SP83-19-04	None	FG	8.16E+04	3.75E-03							
G-423	Gradient measurements	2000	SP99-19-02 to B14-FILTER	None	FG	2.53E+05	6.07E-03							
G-424	Gradient measurements	2000	PN85-06-03 to SP90-06-04	None	FG	4.80E+03	2.37E-02							
G-425	Model dam flume	2001		RN	LM	4.05E-01	8.00E-04	8.00E-04		1				
G-426	Gradient measurements	2000	E08+60	None	FG	4.49E+05	2.31E-04							
G-427	Gradient measurements	2000	E102+00	None	FG	7.53E+05	3.20E-04							
G-428	Gradient measurements	2000	E11+00	None	FG	3.44E+05	4.40E-04							
G-429	Gradient measurements	2000	E18+00	None	FG	4.38E+05	5.39E-04							
G-430	Gradient measurements	2000	E24+00	None	FG	1.60E+06	6.22E-04							
G-431	Gradient measurements	2000	E32+00	None	FG	9.10E+05	7.24E-04							
G-432	Gradient measurements	2000	E40+00	None	FG	3.81E+06	9.51E-04							
G-433	Gradient measurements	2000	E44+00	None	FG	1.32E+06	9.78E-04							
G-434	Gradient measurements	2000	E47+00	None	FG	2.36E+06	9.93E-04							
G-435	Gradient measurements	2000	E53+00	None	FG	1.64E+06	1.19E-03							
G-436	Gradient measurements	2000	E64+00	None	FG	9.64E+05	1.29E-03							
G-437	Gradient measurements	2000	E72+00	None	FG	2.91E+06	1.75E-03							
G-438	Gradient measurements	2000	E75+00	None	FG	6.19E+06	1.78E-03							

Sample / test information							Measured				Assumed for design			
#	Program	Year	Borehole number	Sample type	Test type	Scale volume m^3	k_h cm/s	k_v cm/s	k_u cm/s	k_h/k_v	k_h cm/s	k_v cm/s	k_u cm/s	k_h/k_v
G-439	Gradient measurements	2000	E80+00	None	FG	6.18E+06	1.90E-03							
G-440	Gradient measurements	2000	E85+00	None	FG	4.09E+06	2.14E-03							
G-441	Gradient measurements	2000	E88+00	None	FG	2.62E+06	2.25E-03							
G-442	Gradient measurements	2000	E95+00	None	FG	3.67E+06	4.60E-03							
G-443	Gradient measurements	2000	W04+00	None	FG	5.75E+05	1.99E-04							
G-444	Gradient measurements	2000	W10+00	None	FG	2.92E+05	2.15E-04							
G-445	Gradient measurements	2000	W100+50	None	FG	2.73E+05	2.43E-04							
G-446	Gradient measurements	2000	W15+00	None	FG	1.52E+06	4.26E-04							
G-447	Gradient measurements	2000	W20+00	None	FG	1.97E+05	9.90E-05							
G-448	Gradient measurements	2000	W26+00	None	FG	2.52E+05	9.98E-05							
G-449	Gradient measurements	2000	W31+00	None	FG	3.33E+05	1.15E-04							
G-450	Gradient measurements	2000	W37+00	None	FG	4.44E+05	2.29E-04							
G-451	Gradient measurements	2000	W43+00	None	FG	3.05E+06	3.43E-04							
G-452	Gradient measurements	2000	W55+00	None	FG	1.58E+06	4.90E-04							
G-453	Gradient measurements	2000	W61+00	None	FG	3.48E+06	5.39E-04							
G-454	Gradient measurements	2000	W67+00	None	FG	2.83E+06	6.24E-04							
G-455	Gradient measurements	2000	W72+00	None	FG	2.38E+06	7.00E-04							
G-456	Gradient measurements	2000	W79+00	None	FG	7.53E+05	1.52E-03							

Sample / test information							Measured				Assumed for design			
#	Program	Year	Borehole number	Sample type	Test type	Scale volume m^3	k_h cm/s	k_v cm/s	k_u cm/s	k_h/k_v	k_h cm/s	k_v cm/s	k_u cm/s	k_h/k_v
G-457	Slug test 2000	2000	00-16-05	None	FF	2.00E-02	1.06E-03							
G-458	Slug test 2000	2000	00-16-07	None	FF	2.00E-02	1.22E-04							
G-459	Slug test 2000	2000	00-16-08	None	FF	2.00E-02	3.05E-04							
G-460	Slug test 2000	2000	00-16-09	None	FF	2.00E-02	1.27E-04							
G-461	Slug test 2000	2000	00-16-10	None	FF	2.00E-02	1.45E-04							
G-462	Slug test 2000	2000	00-16-11	None	FF	2.00E-02	2.26E-04							
G-463	Slug test 2000	2000	00-16-12	None	FF	2.00E-02	1.57E-04							
G-464	Slug test 2000	2000	00-16-13	None	FF	2.00E-02	1.28E-04							
G-465	Slug test 2000	2000	00-16-14	None	FF	2.00E-02	6.60E-05							
G-466	Slug test 2000	2000	00-16-15	None	FF	2.00E-02	7.30E-05							
G-467	Slug test 2000	2000	00-16-16	None	FF	2.00E-02	4.52E-05							
G-468	Slug test 2000	2000	00-16-18	None	FF	2.00E-02	4.32E-04							
G-469	Slug test 2000	2000	00-16-19	None	FF	2.00E-02	1.90E-04							
G-470	Slug test 2000	2000	00-16-20	None	FF	2.00E-02	3.14E-04							
G-471	Slug test 2000	2000	00-16-21	None	FF	2.00E-02	5.15E-04							
G-472	Slug test 2000	2000	00-16-22	None	FF	2.00E-02	2.41E-04							
G-473	Slug test 2000	2000	00-16-26	None	FF	2.00E-02	1.62E-04							
G-474	Slug test 2000	2000	00-16-27	None	FF	2.00E-02	1.80E-04							
G-475	Slug test 2000	2000	00-16-28	None	FF	2.00E-02	1.78E-04							
G-476	Slug test 2000	2000	00-16-29	None	FF	2.00E-02	2.09E-04							
G-477	Slug test 2000	2000	00-16-31	None	FF	2.00E-02	2.15E-04							
G-478	Slug test 2000	2000	00-16-32	None	FF	2.00E-02	1.48E-04							
G-479	Slug test 2000	2000	00-16-33	None	FF	2.00E-02	1.59E-04							
G-480	Slug test 2000	2000	00-16-34	None	FF	2.00E-02	2.75E-04							
G-481	Slug test 2000	2000	00-16-35	None	FF	2.00E-02	2.40E-04							
G-482	Slug test 2000	2000	00-16-36	None	FF	2.00E-02	2.55E-04							
G-483	Slug test 2000	2000	00-16-37	None	FF	2.00E-02	1.70E-04							
G-484	Slug test 2000	2000	00-16-38	None	FF	2.00E-02	1.34E-04							
G-485	Slug test 2000	2000	00-16-39	None	FF	2.00E-02	1.33E-04							

Sample / test information							Measured				Assumed for design			
#	Program	Year	Borehole number	Sample type	Test type	Scale volume m^3	k_h cm/s	k_v cm/s	k_u cm/s	k_h/k_v	k_h cm/s	k_v cm/s	k_u cm/s	k_h/k_v
G-486	Slug test 2000	2000	00-16-40	None	FF	2.00E-02	1.16E-04							
G-487	Slug test 2000	2000	00-16-41	None	FF	2.00E-02	1.13E-04							
G-488	Slug test 2000	2000	00-16-42	None	FF	2.00E-02	1.36E-04							
G-489	Slug test 2000	2000	00-16-43	None	FF	2.00E-02	2.35E-04							
G-490	Slug test 2000	2000	00-16-44	None	FF	2.00E-02	1.60E-04							
G-491	Slug test 2000	2000	00-16-45	None	FF	2.00E-02	1.73E-04							
G-492	Slug test 2000	2000	00-16-46	None	FF	2.00E-02	1.53E-04							
G-493	Slug test 2000	2000	00-16-47	None	FF	2.00E-02	3.88E-04							
G-494	Slug test 2000	2000	00-16-48	None	FF	2.00E-02	3.27E-04							
G-495	Slug test 2000	2000	00-16-49	None	FF	2.00E-02	3.26E-04							
G-496	Slug test 2000	2000	00-16-50	None	FF	2.00E-02	2.31E-04							
G-497	Slug test 2000	2000	00-16-51	None	FF	2.00E-02	3.60E-04							
G-498	Slug test 2000	2000	00-16-52	None	FF	2.00E-02	3.19E-04							
G-499	Slug test 2000	2000	00-16-52	None	FF	2.00E-02	2.80E-04							
G-500	Slug test 2000	2000	00-16-53	None	FF	2.00E-02	4.22E-04							
G-501	Slug test 2000	2000	00-16-54	None	FF	2.00E-02	3.64E-04							
G-502	Slug test 2000	2000	00-16-55	None	FF	2.00E-02	2.51E-04							
G-503	Slug test 2000	2000	00-16-56	None	FF	2.00E-02	2.65E-04							
G-504	Slug test 2000	2000	00-16-57	None	FF	2.00E-02	2.12E-04							
G-505	Slug test 2000	2000	00-16-58	None	FF	2.00E-02	2.20E-04							
G-506	Slug test 2000	2000	00-16-59	None	FF	2.00E-02	3.23E-04							
G-507	Slug test 2000	2000	00-16-60	None	FF	2.00E-02	1.23E-04							
G-508	Slug test 2000	2000	00-16-61	None	FF	2.00E-02	2.69E-04							
G-509	Slug test 2000	2000	00-16-62	None	FF	2.00E-02	2.38E-04							
G-510	Slug test 2000	2000	00-16-63	None	FF	2.00E-02	1.55E-04							
G-511	Slug test 2000	2000	00-16-64	None	FF	2.00E-02	2.78E-04							
G-512	Slug test 2000	2000	00-16-65	None	FF	2.00E-02	3.81E-04							
G-513	Slug test 2000	2000	00-16-67	None	FF	2.00E-02	1.08E-04							
G-514	Slug test 2000	2000	00-16-68	None	FF	2.00E-02	2.07E-04							

Sample / test information							Measured				Assumed for design			
#	Program	Year	Borehole number	Sample type	Test type	Scale volume m^3	k_h cm/s	k_v cm/s	k_u cm/s	k_h/k_v	k_h cm/s	k_v cm/s	k_u cm/s	k_h/k_v
G-515	Slug test 2000	2000	00-16-69	None	FF	2.00E-02	3.12E-04							
G-516	Slug test 2000	2000	00-16-70	None	FF	2.00E-02	5.22E-04							
G-517	Slug test 2000	2000	00-16-71	None	FF	2.00E-02	2.61E-04							
G-518	Slug test 2000	2000	00-16-72	None	FF	2.00E-02	1.45E-04							
G-519	Slug test 2000	2000	00-16-73	None	FF	2.00E-02	1.66E-04							
G-520	Slug test 2000	2000	00-16-74	None	FF	2.00E-02	1.37E-04							
G-521	Slug test 2000	2000	00-16-75	None	FF	2.00E-02	2.26E-04							
G-522	Slug test 2000	2000	00-16-77	None	FF	2.00E-02	3.53E-04							
G-523	Slug test 2000	2000	00-16-78	None	FF	2.00E-02	6.84E-04							
G-524	Slug test 2000	2000	00-16-79	None	FF	2.00E-02	2.52E-04							
G-525	Slug test 2000	2000	00-16-82	None	FF	2.00E-02	2.72E-04							
G-526	Slug test 2000	2000	00-16-83	None	FF	2.00E-02	1.55E-04							
G-527	Slug test 2000	2000	00-16-84	None	FF	2.00E-02	2.06E-04							
G-528	Slug test 2000	2000	00-16-85	None	FF	2.00E-02	6.64E-04							
G-529	Slug test 2000	2000	00-16-87	None	FF	2.00E-02	2.96E-04							
G-530	Slug test 2000	2000	00-16-88	None	FF	2.00E-02	9.37E-05							
G-531	Slug test 2000	2000	00-16-89	None	FF	2.00E-02	8.46E-05							
G-532	Slug test 2000	2000	00-16-90	None	FF	2.00E-02	1.01E-04							
G-533	Slug test 2000	2000	00-16-92	None	FF	2.00E-02	7.87E-05							
G-534	Slug test 2000	2000	00-16-93	None	FF	2.00E-02	8.57E-05							
G-535	Slug test 2000	2000	00-16-94	None	FF	2.00E-02	6.61E-05							
G-536	Slug test 2000	2000	00-17-02	None	FF	2.00E-02	6.18E-04							
G-537	Slug test 2000	2000	00-17-03	None	FF	2.00E-02	2.16E-06							
G-538	Slug test 2000	2000	00-20-07	None	FF	2.00E-02	1.33E-04							
G-539	Slug test 2000	2000	00-20-08	None	FF	2.00E-02	5.68E-04							
G-540	Slug test 2000	2000	00-22-02	None	FF	2.00E-02	1.36E-04							
G-541	Slug test 2000	2000	00-22-05	None	FF	2.00E-02	6.41E-05							
G-542	Slug test 2000	2000	00-22-06	None	FF	2.00E-02	5.76E-06							
G-543	Slug test 2000	2000	81-03-01	None	FF	2.00E-02	2.20E-04							

Sample / test information							Measured				Assumed for design			
#	Program	Year	Borehole number	Sample type	Test type	Scale volume m^3	k_h cm/s	k_v cm/s	k_u cm/s	k_h/k_v	k_h cm/s	k_v cm/s	k_u cm/s	k_h/k_v
G-544	Slug test 2000	2000	81-03-04	None	FF	2.00E-02	4.77E-04							
G-545	Slug test 2000	2000	88-21-06	None	FF	2.00E-02	3.79E-05							
G-546	Slug test 2000	2000	92-11-04	None	FF	2.00E-02	9.28E-04							
G-547	Slug test 2000	2000	94-02-01	None	FF	2.00E-02	2.34E-04							
G-548	Slug test 2000	2000	94-03-01	None	FF	2.00E-02	4.14E-04							
G-549	Slug test 2000	2000	94-04-01	None	FF	2.00E-02	6.94E-05							
G-550	Slug test 2000	2000	94-07-01	None	FF	2.00E-02	2.64E-04							
G-551	Slug test 2000	2000	95-31-06	None	FF	2.00E-02	2.26E-04							
G-552	Slug test 2000	2000	95-31-08	None	FF	2.00E-02	2.01E-04							
G-553	Slug test 2000	2000	95-50-15	None	FF	2.00E-02	4.14E-04							
G-554	Slug test 2000	2000	95-50-16	None	FF	2.00E-02	2.77E-04							
G-555	Slug test 2000	2000	95-51-05	None	FF	2.00E-02	1.31E-04							
G-556	Slug test 2000	2000	95-51-06	None	FF	2.00E-02	1.68E-04							
G-557	Slug test 2000	2000	96-16-03	None	FF	2.00E-02	4.14E-04							
G-558	Slug test 2000	2000	96-16-06	None	FF	2.00E-02	5.73E-04							
G-559	Slug test 2000	2000	96-16-07	None	FF	2.00E-02	9.27E-04							
G-560	Slug test 2000	2000	96-16-08	None	FF	2.00E-02	5.17E-04							
G-561	Slug test 2000	2000	96-30-04	None	FF	2.00E-02	2.29E-04							
G-562	Slug test 2000	2000	96-30-05	None	FF	2.00E-02	3.29E-04							
G-563	Slug test 2000	2000	96-31-10	None	FF	2.00E-02	8.83E-05							
G-564	Slug test 2000	2000	96-31-11	None	FF	2.00E-02	1.49E-04							
G-565	Slug test 2000	2000	96-51-01	None	FF	2.00E-02	8.84E-04							
G-566	Slug test 2000	2000	96-51-03	None	FF	2.00E-02	1.32E-04							
G-567	Slug test 2000	2000	96-51-04	None	FF	2.00E-02	3.62E-04							
G-568	Slug test 2000	2000	96-51-05	None	FF	2.00E-02	2.84E-04							
G-569	Slug test 2000	2000	97-16-19	None	FF	2.00E-02	5.41E-05							
G-570	Slug test 2000	2000	97-16-20	None	FF	2.00E-02	1.00E-04							
G-571	Slug test 2000	2000	98-04-01	None	FF	2.00E-02	4.24E-04							
G-572	Slug test 2000	2000	98-08-01	None	FF	2.00E-02	2.64E-04							

Sample / test information							Measured				Assumed for design			
#	Program	Year	Borehole number	Sample type	Test type	Scale volume m^3	k_h cm/s	k_v cm/s	k_u cm/s	k_h/k_v	k_h cm/s	k_v cm/s	k_u cm/s	k_h/k_v
G-573	Slug test 2000	2000	98-16-10	None	FF	2.00E-02	2.41E-04							
G-574	Slug test 2000	2000	98-16-11	None	FF	2.00E-02	6.10E-04							
G-575	Slug test 2000	2000	98-17-02	None	FF	2.00E-02	2.56E-04							
G-576	Slug test 2000	2000	98-17-05	None	FF	2.00E-02	5.04E-04							
G-577	Slug test 2000	2000	98-18-02	None	FF	2.00E-02	4.93E-04							
G-578	Slug test 2000	2000	98-49-01	None	FF	2.00E-02	6.55E-05							
G-579	Slug test 2000	2000	98-49-02	None	FF	2.00E-02	5.86E-05							
G-580	Slug test 2000	2000	98-49-03	None	FF	2.00E-02	1.65E-04							
G-581	Slug test 2000	2000	98-49-04	None	FF	2.00E-02	3.71E-04							
G-582	Slug test 2000	2000	99-16-24	None	FF	2.00E-02	1.39E-04							
G-583	Slug test 2000	2000	99-16-25	None	FF	2.00E-02	9.97E-05							
G-584	Slug test 2000	2000	99-16-26	None	FF	2.00E-02	1.09E-04							
G-585	Slug test 2000	2000	99-16-27	None	FF	2.00E-02	1.02E-04							
G-586	Slug test 2000	2000	99-16-30	None	FF	2.00E-02	2.05E-04							
G-587	Slug test 2000	2000	99-16-31	None	FF	2.00E-02	1.20E-04							
G-588	Slug test 2000	2000	99-16-33	None	FF	2.00E-02	4.81E-05							
G-589	Slug test 2000	2000	99-16-34	None	FF	2.00E-02	1.68E-04							
G-590	Slug test 2000	2000	99-16-35	None	FF	2.00E-02	1.25E-05							
G-591	Slug test 2000	2000	99-16-36	None	FF	2.00E-02	6.53E-05							
G-592	Slug test 2000	2000	99-16-39	None	FF	2.00E-02	7.70E-05							
G-593	Slug test 2000	2000	99-16-42	None	FF	2.00E-02	4.21E-05							
G-594	Slug test 2000	2000	99-16-49	None	FF	2.00E-02	1.86E-04							
G-595	Slug test 2000	2000	99-16-50	None	FF	2.00E-02	2.93E-04							
G-596	Slug test 2000	2000	99-48-01	None	FF	2.00E-02	1.42E-04							
G-597	Slug test 2000	2000	99-48-02	None	FF	2.00E-02	1.11E-04							
G-598	Slug test 2000	2000	99-48-03	None	FF	2.00E-02	1.74E-04							
G-599	Slug test 2000	2000	99-48-04	None	FF	2.00E-02	1.71E-04							
G-600	Guelph Infiltrations	2000		None	FI	5.00E-03		1.07E-04						
G-601	Guelph Infiltrations	2000		None	FI	5.00E-03		1.47E-04						

Sample / test information							Measured				Assumed for design			
#	Program	Year	Borehole number	Sample type	Test type	Scale volume m^3	k_h cm/s	k_v cm/s	k_u cm/s	k_h/k_v	k_h cm/s	k_v cm/s	k_u cm/s	k_h/k_v
G-602	Guelph Infiltrations	2000		None	FI	5.00E-03		1.66E-04						
G-603	Guelph Infiltrations	2000		None	FI	5.00E-03		3.38E-04						
G-604	Guelph Infiltrations	2000		None	FI	5.00E-03		3.68E-04						
G-605	Guelph Infiltrations	2000		None	FI	5.00E-03		3.73E-04						
G-606	Guelph Infiltrations	2000		None	FI	5.00E-03		4.44E-04						
G-607	Guelph Infiltrations	2000		None	FI	5.00E-03		4.70E-04						
G-608	Guelph Infiltrations	2000		None	FI	5.00E-03		4.77E-04						
G-609	Guelph Infiltrations	2000		None	FI	5.00E-03		5.35E-04						
G-610	Guelph Infiltrations	2000		None	FI	5.00E-03		5.71E-04						
G-611	Guelph Infiltrations	2000		None	FI	5.00E-03		6.39E-04						
G-612	Guelph Infiltrations	2000		None	FI	5.00E-03		6.48E-04						
G-613	Guelph Infiltrations	2000		None	FI	5.00E-03		7.56E-04						
G-614	Guelph Infiltrations	2000		None	FI	5.00E-03		9.64E-04						
G-615	Guelph Infiltrations	2000		None	FI	5.00E-03		1.12E-03						
G-616	Guelph Infiltrations	2000		None	FI	5.00E-03		1.35E-03						
G-617	Guelph Infiltrations	2000		None	FI	5.00E-03		1.37E-03						
G-618	Guelph Infiltrations	2000		None	FI	5.00E-03		1.45E-03						
G-619	Guelph Infiltrations	2000		None	FI	5.00E-03		1.77E-03						
G-620	Guelph Infiltrations	2000		None	FI	5.00E-03		1.85E-03						
G-621	Guelph Infiltrations	2000		None	FI	5.00E-03		2.01E-03						
G-622	Guelph Infiltrations	2000		None	FI	5.00E-03		2.28E-03						
G-623	Guelph Infiltrations	2000		None	FI	5.00E-03		2.32E-03						
G-624	Guelph Infiltrations	2000		None	FI	5.00E-03		2.81E-03						
G-625	Guelph Infiltrations	2000		None	FI	5.00E-03		4.59E-03						
G-626	Coffee Can Percolation Tests	2000	None	FP	1.86E-03			2.37E-03						
G-627	Coffee Can Percolation Tests	2000	None	FP	1.86E-03			4.18E-03						
G-628	Coffee Can Percolation Tests	2000	None	FP	1.86E-03			1.86E-03						

Sample / test information							Measured				Assumed for design			
#	Program	Year	Borehole number	Sample type	Test type	Scale volume m^3	k_h cm/s	k_v cm/s	k_u cm/s	k_h/k_v	k_h cm/s	k_v cm/s	k_u cm/s	k_h/k_v
G-629	Coffee Can Percolation Tests	2000		None	FP	1.86E-03			2.05E-03					
G-630	Coffee Can Percolation Tests	2000		None	FP	1.86E-03			1.51E-03					
G-631	Coffee Can Percolation Tests	2000		None	FP	1.86E-03			1.49E-03					
G-632	Coffee Can Percolation Tests	2000		None	FP	1.86E-03			1.41E-03					
G-633	Coffee Can Percolation Tests	2000		None	FP	1.86E-03			3.57E-03					
G-634	Coffee Can Percolation Tests	2000		None	FP	1.86E-03			4.47E-03					
G-635	Coffee Can Percolation Tests	2000		None	FP	1.86E-03			3.71E-03					
G-636	Coffee Can Percolation Tests	2000		None	FP	1.86E-03			3.97E-03					
G-637	Coffee Can Percolation Tests	2000		None	FP	1.86E-03			3.16E-03					
G-638	Coffee Can Percolation Tests	2000		None	FP	1.86E-03			3.42E-03					
G-639	Coffee Can Percolation Tests	2000		None	FP	1.86E-03			3.60E-03					
G-640	Coffee Can Percolation Tests	2000		None	FP	1.86E-03			3.45E-03					
G-641	Coffee Can Percolation Tests	2000		None	FP	1.86E-03			2.91E-03					
G-642	Coffee Can Percolation Tests	2000		None	FP	1.86E-03			2.03E-03					
G-643	Coffee Can Percolation Tests	2000		None	FP	1.86E-03			2.47E-03					
G-644	Coffee Can Percolation Tests	2000		None	FP	1.86E-03			2.02E-03					
G-645	Coffee Can Percolation Tests	2000		None	FP	1.86E-03			3.32E-03					
G-646	Coffee Can Percolation Tests	2000		None	FP	1.86E-03			2.84E-03					

Sample / test information							Measured				Assumed for design			
#	Program	Year	Borehole number	Sample type	Test type	Scale volume m^3	k_h cm/s	k_v cm/s	k_u cm/s	k_h/k_v	k_h cm/s	k_v cm/s	k_u cm/s	k_h/k_v
G-647	Coffee Can Percolation Tests	2000		None	FP	1.86E-03			2.72E-03					
G-648	Coffee Can Percolation Tests	2000		None	FP	1.86E-03			1.48E-03					
G-649	Coffee Can Percolation Tests	2000		None	FP	1.86E-03			2.29E-03					
G-650	Coffee Can Percolation Tests	2000		None	FP	1.86E-03			7.62E-04					
G-651	Coffee Can Percolation Tests	2000		None	FP	1.86E-03			3.44E-05					
G-652	Coffee Can Percolation Tests	2000		None	FP	1.86E-03			1.41E-03					
G-653	Coffee Can Percolation Tests	2000		None	FP	1.86E-03			6.92E-04					
G-654	Coffee Can Percolation Tests	2000		None	FP	1.86E-03			1.82E-03					
G-655	Coffee Can Percolation Tests	2000		None	FP	1.86E-03			3.07E-03					
G-656	Coffee Can Percolation Tests	2000		None	FP	1.86E-03			1.08E-03					
G-657	Coffee Can Percolation Tests	2000		None	FP	1.86E-03			2.03E-03					
G-658	Coffee Can Percolation Tests	2000		None	FP	1.86E-03			7.10E-04					
G-659	Coffee Can Percolation Tests	2000		None	FP	1.86E-03			1.96E-03					
G-660	Coffee Can Percolation Tests	2000		None	FP	1.86E-03			2.96E-03					
G-661	Coffee Can Percolation Tests	2000		None	FP	1.86E-03			5.45E-03					
G-662	Coffee Can Percolation Tests	2000		None	FP	1.86E-03			3.37E-03					
G-663	Coffee Can Percolation Tests	2000		None	FP	1.86E-03			5.18E-03					
G-664	Coffee Can Percolation Tests	2000		None	FP	1.86E-03			6.84E-03					

Sample / test information							Measured				Assumed for design			
#	Program	Year	Borehole number	Sample type	Test type	Scale volume m^3	k_h cm/s	k_v cm/s	k_u cm/s	k_h/k_v	k_h cm/s	k_v cm/s	k_u cm/s	k_h/k_v
G-665	Coffee Can Percolation Tests	2000		None	FP	1.86E-03			5.73E-03					
G-666	Coffee Can Percolation Tests	2000		None	FP	1.86E-03			3.60E-03					
G-667	Coffee Can Percolation Tests	2000		None	FP	1.86E-03			2.15E-03					
G-668	Coffee Can Percolation Tests	2000		None	FP	1.86E-03			3.45E-03					
G-669	Coffee Can Percolation Tests	2000		None	FP	1.86E-03			2.25E-03					
G-670	Coffee Can Percolation Tests	2000		None	FP	1.86E-03			2.98E-03					
G-671	Coffee Can Percolation Tests	2000		None	FP	1.86E-03			3.84E-05					
G-672	Coffee Can Percolation Tests	2000		None	FP	1.86E-03			1.04E-03					
G-673	Coffee Can Percolation Tests	2000		None	FP	1.86E-03			2.98E-03					
G-674	Coffee Can Percolation Tests	2000		None	FP	1.86E-03			1.96E-03					
G-675	Coffee Can Percolation Tests	2000		None	FP	1.86E-03			5.27E-03					
G-676	Coffee Can Percolation Tests	2000		None	FP	1.86E-03			5.18E-03					
G-677	Coffee Can Percolation Tests	2000		None	FP	1.86E-03			2.27E-03					
G-678	Coffee Can Percolation Tests	2000		None	FP	1.86E-03			1.49E-03					
G-679	Coffee Can Percolation Tests	2000		None	FP	1.86E-03			3.14E-03					
G-680	Coffee Can Percolation Tests	2000		None	FP	1.86E-03			2.37E-03					
G-681	Coffee Can Percolation Tests	2000		None	FP	1.86E-03			1.81E-03					
G-682	Coffee Can Percolation Tests	2000		None	FP	1.86E-03			1.82E-03					

Sample / test information							Measured				Assumed for design			
#	Program	Year	Borehole number	Sample type	Test type	Scale volume m^3	k_h cm/s	k_v cm/s	k_u cm/s	k_h/k_v	k_h cm/s	k_v cm/s	k_u cm/s	k_h/k_v
G-683	Coffee Can Percolation Tests	2000		None	FP	1.86E-03			1.84E-03					
G-684	Coffee Can Percolation Tests	2000		None	FP	1.86E-03			4.18E-03					
G-685	Coffee Can Percolation Tests	2000		None	FP	1.86E-03			2.98E-03					
G-686	Coffee Can Percolation Tests	2000		None	FP	1.86E-03			3.07E-03					
G-687	Coffee Can Percolation Tests	2000		None	FP	1.86E-03			2.27E-03					
G-688	Coffee Can Percolation Tests	2000		None	FP	1.86E-03			2.36E-03					
G-689	Coffee Can Percolation Tests	2000		None	FP	1.86E-03			3.77E-03					
G-690	Coffee Can Percolation Tests	2000		None	FP	1.86E-03			4.35E-03					
G-691	Coffee Can Percolation Tests	2000		None	FP	1.86E-03			2.78E-03					
G-692	Coffee Can Percolation Tests	2000		None	FP	1.86E-03			2.87E-03					
G-693	Coffee Can Percolation Tests	2000		None	FP	1.86E-03			4.21E-03					
G-694	Coffee Can Percolation Tests	2000		None	FP	1.86E-03			1.51E-03					
G-695	Coffee Can Percolation Tests	2000		None	FP	1.86E-03			1.08E-03					
G-696	Coffee Can Percolation Tests	2000		None	FP	1.86E-03			4.50E-03					
G-697	Coffee Can Percolation Tests	2000		None	FP	1.86E-03			1.46E-03					
G-698	Coffee Can Percolation Tests	2000		None	FP	1.86E-03			2.22E-03					
G-699	Coffee Can Percolation Tests	2000		None	FP	1.86E-03			2.55E-03					
G-700	Coffee Can Percolation Tests	2000		None	FP	1.86E-03			5.83E-03					

Sample / test information							Measured				Assumed for design			
#	Program	Year	Borehole number	Sample type	Test type	Scale volume m^3	k_h cm/s	k_v cm/s	k_u cm/s	k_h/k_v	k_h cm/s	k_v cm/s	k_u cm/s	k_h/k_v
G-701	Coffee Can Percolation Tests	2000		None	FP	1.86E-03			3.60E-03					
G-702	Coffee Can Percolation Tests	2000		None	FP	1.86E-03			1.12E-03					
G-703	Coffee Can Percolation Tests	2000		None	FP	1.86E-03			1.79E-03					
G-704	Coffee Can Percolation Tests	2000		None	FP	1.86E-03			2.45E-03					
G-705	Coffee Can Percolation Tests	2000		None	FP	1.86E-03			3.37E-05					
G-706	Coffee Can Percolation Tests	2000		None	FP	1.86E-03			7.62E-04					
G-707	Coffee Can Percolation Tests	2000		None	FP	1.86E-03			1.39E-03					
G-708	Coffee Can Percolation Tests	2000		None	FP	1.86E-03			1.27E-03					
G-709	Coffee Can Percolation Tests	2000		None	FP	1.86E-03			1.14E-03					
G-710	Coffee Can Percolation Tests	2000		None	FP	1.86E-03			3.57E-03					
G-711	Coffee Can Percolation Tests	2000		None	FP	1.86E-03			2.74E-03					
G-712	Coffee Can Percolation Tests	2000		None	FP	1.86E-03			1.91E-03					
G-713	Coffee Can Percolation Tests	2000		None	FP	1.86E-03			1.61E-03					
G-714	Coffee Can Percolation Tests	2000		None	FP	1.86E-03			7.91E-04					
G-715	Coffee Can Percolation Tests	2000		None	FP	1.86E-03			1.42E-03					
G-716	Coffee Can Percolation Tests	2000		None	FP	1.86E-03			1.51E-03					
G-717	Coffee Can Percolation Tests	2000		None	FP	1.86E-03			3.66E-04					
G-718	Coffee Can Percolation Tests	2000		None	FP	1.86E-03			3.49E-04					

Sample / test information							Measured				Assumed for design			
#	Program	Year	Borehole number	Sample type	Test type	Scale volume m^3	k_h cm/s	k_v cm/s	k_u cm/s	k_h/k_v	k_h cm/s	k_v cm/s	k_u cm/s	k_h/k_v
G-719	Coffee Can Percolation Tests	2000		None	FP	1.86E-03			2.03E-03					
G-720	Coffee Can Percolation Tests	2000		None	FP	1.86E-03			1.19E-03					
G-721	Coffee Can Percolation Tests	2000		None	FP	1.86E-03			2.18E-03					
G-722	Coffee Can Percolation Tests	2000		None	FP	1.86E-03			1.97E-03					
G-723	Coffee Can Percolation Tests	2000		None	FP	1.86E-03			1.01E-03					
G-724	Coffee Can Percolation Tests	2000		None	FP	1.86E-03			6.83E-04					
G-725	Coffee Can Percolation Tests	2000		None	FP	1.86E-03			3.34E-03					
G-726	Coffee Can Percolation Tests	2000		None	FP	1.86E-03			3.37E-03					
G-727	Coffee Can Percolation Tests	2000		None	FP	1.86E-03			1.01E-02					
G-728	Coffee Can Percolation Tests	2000		None	FP	1.86E-03			5.89E-03					
G-729	Coffee Can Percolation Tests	2000		None	FP	1.86E-03			9.21E-03					
G-730	Coffee Can Percolation Tests	2000		None	FP	1.86E-03			7.09E-03					
G-731	Coffee Can Percolation Tests	2000		None	FP	1.86E-03			1.02E-02					
G-732	Coffee Can Percolation Tests	2000		None	FP	1.86E-03			6.74E-04					
G-733	Coffee Can Percolation Tests	2000		None	FP	1.86E-03			1.82E-03					
G-734	Coffee Can Percolation Tests	2000		None	FP	1.86E-03			3.59E-04					
G-735	Coffee Can Percolation Tests	2000		None	FP	1.86E-03			6.19E-03					
G-736	Coffee Can Percolation Tests	2000		None	FP	1.86E-03			2.60E-03					

Sample / test information							Measured				Assumed for design			
#	Program	Year	Borehole number	Sample type	Test type	Scale volume m^3	k_h cm/s	k_v cm/s	k_a cm/s	k_h/k_v	k_h cm/s	k_v cm/s	k_a cm/s	k_h/k_v
G-737	Coffee Can Percolation Tests	2000		None	FP	1.86E-03			1.73E-03					
G-738	Coffee Can Percolation Tests	2000		None	FP	1.86E-03			4.24E-03					
G-739	Coffee Can Percolation Tests	2000		None	FP	1.86E-03			6.36E-03					
G-740	Coffee Can Percolation Tests	2000		None	FP	1.86E-03			7.26E-03					
G-741	Coffee Can Percolation Tests	2000		None	FP	1.86E-03			7.26E-03					
G-742	Coffee Can Percolation Tests	2000		None	FP	1.86E-03			8.17E-03					
G-743	Coffee Can Percolation Tests	2000		None	FP	1.86E-03			7.02E-03					
G-744	Coffee Can Percolation Tests	2000		None	FP	1.86E-03			3.78E-03					
G-745	Coffee Can Percolation Tests	2000		None	FP	1.86E-03			7.75E-03					
G-746	Coffee Can Percolation Tests	2000		None	FP	1.86E-03			6.50E-03					
G-747	Coffee Can Percolation Tests	2000		None	FP	1.86E-03			4.02E-03					
G-748	Coffee Can Percolation Tests	2000		None	FP	1.86E-03			2.94E-03					
G-749	Coffee Can Percolation Tests	2000		None	FP	1.86E-03			1.94E-03					
G-750	Coffee Can Percolation Tests	2000		None	FP	1.86E-03			6.50E-03					
G-751	Coffee Can Percolation Tests	2000		None	FP	1.86E-03			9.67E-03					
G-752	Coffee Can Percolation Tests	2000		None	FP	1.86E-03			6.14E-03					
G-753	Coffee Can Percolation Tests	2000		None	FP	1.86E-03			1.15E-02					
G-754	Coffee Can Percolation Tests	2000		None	FP	1.86E-03			5.73E-03					

Sample / test information							Measured				Assumed for design			
#	Program	Year	Borehole number	Sample type	Test type	Scale volume m^3	k_h cm/s	k_v cm/s	k_u cm/s	k_h/k_v	k_h cm/s	k_v cm/s	k_u cm/s	k_h/k_v
G-755	Coffee Can Percolation Tests	2000		None	FP	1.86E-03			6.50E-03					
G-756	Coffee Can Percolation Tests	2000		None	FP	1.86E-03			3.19E-03					
G-757	Coffee Can Percolation Tests	2000		None	FP	1.86E-03			1.96E-03					
G-758	Coffee Can Percolation Tests	2000		None	FP	1.86E-03			8.11E-03					
G-759	Coffee Can Percolation Tests	2000		None	FP	1.86E-03			2.78E-03					
G-760	Coffee Can Percolation Tests	2000		None	FP	1.86E-03			7.89E-03					
G-761	Coffee Can Percolation Tests	2000		None	FP	1.86E-03			1.23E-02					
G-762	Coffee Can Percolation Tests	2000		None	FP	1.86E-03			8.54E-03					
G-763	Coffee Can Percolation Tests	2000		None	FP	1.86E-03			7.59E-03					
G-764	Coffee Can Percolation Tests	2000		None	FP	1.86E-03			6.09E-03					
G-765	Coffee Can Percolation Tests	2000		None	FP	1.86E-03			5.85E-03					
G-766	Coffee Can Percolation Tests	2000		None	FP	1.86E-03			5.40E-03					
G-767	Coffee Can Percolation Tests	2000		None	FP	1.86E-03			8.17E-03					
G-768	Coffee Can Percolation Tests	2000		None	FP	1.86E-03			5.54E-03					
G-769	Coffee Can Percolation Tests	2000		None	FP	1.86E-03			7.64E-03					
G-770	Coffee Can Percolation Tests	2000		None	FP	1.86E-03			5.68E-03					
G-771	Coffee Can Percolation Tests	2000		None	FP	1.86E-03			5.85E-03					
G-772	Coffee Can Percolation Tests	2000		None	FP	1.86E-03			5.05E-03					

Sample / test information							Measured				Assumed for design			
#	Program	Year	Borehole number	Sample type	Test type	Scale volume m^3	k_h cm/s	k_v cm/s	k_u cm/s	k_h/k_v	k_h cm/s	k_v cm/s	k_u cm/s	k_h/k_v
G-773	Coffee Can Percolation Tests	2000		None	FP	1.86E-03			5.85E-03					
G-774	Coffee Can Percolation Tests	2000		None	FP	1.86E-03			5.67E-03					
G-775	Coffee Can Percolation Tests	2000		None	FP	1.86E-03			4.24E-03					
G-776	Coffee Can Percolation Tests	2000		None	FP	1.86E-03			5.36E-03					
G-777	Coffee Can Percolation Tests	2000		None	FP	1.86E-03			7.20E-03					
G-778	Coffee Can Percolation Tests	2000		None	FP	1.86E-03			6.78E-03					
G-779	Coffee Can Percolation Tests	2000		None	FP	1.86E-03			6.50E-03					
G-780	Coffee Can Percolation Tests	2000		None	FP	1.86E-03			6.96E-03					
G-781	Coffee Can Percolation Tests	2000		None	FP	1.86E-03			9.95E-03					
G-782	Coffee Can Percolation Tests	2000		None	FP	1.86E-03			8.62E-03					
G-783	Coffee Can Percolation Tests	2000		None	FP	1.86E-03			5.28E-03					
G-784	Coffee Can Percolation Tests	2000		None	FP	1.86E-03			1.36E-03					
G-785	Coffee Can Percolation Tests	2000		None	FP	1.86E-03			6.96E-03					
G-786	Coffee Can Percolation Tests	2000		None	FP	1.86E-03			3.93E-03					
G-787	Coffee Can Percolation Tests	2000		None	FP	1.86E-03			5.24E-03					
G-788	Coffee Can Percolation Tests	2000		None	FP	1.86E-03			6.74E-03					
G-789	Coffee Can Percolation Tests	2000		None	FP	1.86E-03			3.84E-03					
G-790	Coffee Can Percolation Tests	2000		None	FP	1.86E-03			5.68E-03					

Sample / test information							Measured				Assumed for design			
#	Program	Year	Borehole number	Sample type	Test type	Scale volume m^3	k_h cm/s	k_v cm/s	k_u cm/s	k_h/k_v	k_h cm/s	k_v cm/s	k_u cm/s	k_h/k_v
G-791	Coffee Can Percolation Tests	2000		None	FP	1.86E-03			6.34E-03					
G-792	Coffee Can Percolation Tests	2000		None	FP	1.86E-03			9.06E-03					
G-793	Coffee Can Percolation Tests	2000		None	FP	1.86E-03			3.19E-03					
G-794	Coffee Can Percolation Tests	2000		None	FP	1.86E-03			6.77E-03					
G-795	Coffee Can Percolation Tests	2000		None	FP	1.86E-03			1.13E-02					
G-796	Coffee Can Percolation Tests	2000		None	FP	1.86E-03			9.77E-03					
G-797	Coffee Can Percolation Tests	2000		None	FP	1.86E-03			5.89E-03					
G-798	Coffee Can Percolation Tests	2000		None	FP	1.86E-03			7.82E-03					
G-799	Coffee Can Percolation Tests	2000		None	FP	1.86E-03			6.25E-03					
G-800	Coffee Can Percolation Tests	2000		None	FP	1.86E-03			4.33E-03					
G-801	Coffee Can Percolation Tests	2000		None	FP	1.86E-03			6.84E-03					
G-802	Coffee Can Percolation Tests	2000		None	FP	1.86E-03			4.77E-03					
G-803	Coffee Can Percolation Tests	2000		None	FP	1.86E-03			6.03E-03					
G-804	Coffee Can Percolation Tests	2000		None	FP	1.86E-03			7.22E-03					
G-805	Coffee Can Percolation Tests	2000		None	FP	1.86E-03			8.92E-03					
G-806	Coffee Can Percolation Tests	2000		None	FP	1.86E-03			7.42E-03					
G-807	Coffee Can Percolation Tests	2000		None	FP	1.86E-03			1.09E-02					
G-808	Coffee Can Percolation Tests	2000		None	FP	1.86E-03			9.49E-03					

Sample / test information							Measured				Assumed for design			
#	Program	Year	Borehole number	Sample type	Test type	Scale volume m^3	k_h cm/s	k_v cm/s	k_u cm/s	k_h/k_v	k_h cm/s	k_v cm/s	k_u cm/s	k_h/k_v
G-809	Coffee Can Percolation Tests	2000		None	FP	1.86E-03			7.33E-03					
G-810	Coffee Can Percolation Tests	2000		None	FP	1.86E-03			7.02E-03					
G-811	Coffee Can Percolation Tests	2000		None	FP	1.86E-03			7.09E-03					
G-812	Coffee Can Percolation Tests	2000		None	FP	1.86E-03			6.65E-03					
G-813	Coffee Can Percolation Tests	2000		None	FP	1.86E-03			7.75E-03					
G-814	Coffee Can Percolation Tests	2000		None	FP	1.86E-03			7.96E-03					
G-815	Coffee Can Percolation Tests	2000		None	FP	1.86E-03			1.02E-02					
G-816	Coffee Can Percolation Tests	2000		None	FP	1.86E-03			6.67E-03					
G-817	Coffee Can Percolation Tests	2000		None	FP	1.86E-03			9.04E-03					
G-818	Coffee Can Percolation Tests	2000		None	FP	1.86E-03			1.01E-02					
G-819	Coffee Can Percolation Tests	2000		None	FP	1.86E-03			7.96E-03					
G-820	Coffee Can Percolation Tests	2000		None	FP	1.86E-03			9.04E-03					
G-821	Coffee Can Percolation Tests	2000		None	FP	1.86E-03			6.90E-03					
G-822	Coffee Can Percolation Tests	2000		None	FP	1.86E-03			8.11E-03					
G-823	Coffee Can Percolation Tests	2000		None	FP	1.86E-03			7.68E-03					
G-824	Coffee Can Percolation Tests	2000		None	FP	1.86E-03			4.33E-03					
G-825	Frozen Core Lab Tests 2000	2000	5H	FH	LH	8.63E-05	3.95E-04							
G-826	Frozen Core Lab Tests 2000	2000	5V	FV	LH	8.81E-05		4.82E-04						

Sample / test information							Measured				Assumed for design			
#	Program	Year	Borehole number	Sample type	Test type	Scale volume m^3	k_h cm/s	k_v cm/s	k_u cm/s	k_h/k_v	k_h cm/s	k_v cm/s	k_u cm/s	k_h/k_v
G-827	Frozen Core Lab Tests 2000	2000	8H	FH	LH	1.02E-04	6.49E-05							
G-828	Frozen Core Lab Tests 2000	2000	8H-2	FH	LH	9.72E-05	3.96E-04							
G-829	Frozen Core Lab Tests 2000	2000	8V	FV	LH	1.01E-04		7.89E-04						
G-830	Frozen Core Lab Tests 2000	2000	8V-2	FV	LH	1.11E-04		1.14E-03						
G-831	Frozen Core Lab Tests 2000	2000	11H	FH	LH	9.62E-05	9.60E-05							
G-832	Frozen Core Lab Tests 2000	2000	11V	FV	LH	7.80E-05		6.38E-05						
G-833	Frozen Core Lab Tests 2000	2000	12H	FH	LH	9.09E-05	2.57E-04							
G-834	Frozen Core Lab Tests 2000	2000	13H	FH	LH	8.53E-05	2.11E-04							
G-835	Frozen Core Lab Tests 2000	2000	13V	FV	LH	8.18E-05		6.38E-05						
G-836	Frozen Core Lab Tests 2000	2000	14H	FH	LH	8.39E-05	8.04E-04							
G-837	Frozen Core Lab Tests 2000	2000	14V	FV	LH	8.63E-05		3.06E-04						
G-838	Frozen Core Lab Tests 2000	2000	15V	FV	LH	8.97E-05		1.25E-04						
G-839	Frozen Core Lab Tests 2000	2000	17H	FH	LH	9.30E-05	1.93E-04							
G-840	Frozen Core Lab Tests 2000	2000	17V	FV	LH	8.62E-05		4.54E-05						
G-841	Frozen Core Lab Tests 2000	2000	19H	FH	LH	1.03E-04	5.53E-05							
G-842	Frozen Core Lab Tests 2000	2000	19V	FV	LH	9.18E-05		6.27E-04						
G-843	Frozen Core Lab Tests 2000	2000	20H	FH	LH	1.01E-04	3.15E-04							
G-844	Frozen Core Lab Tests 2000	2000	20V	FV	LH	9.80E-05		6.69E-04						

Sample / test information							Measured				Assumed for design			
#	Program	Year	Borehole number	Sample type	Test type	Scale volume m^3	k_h cm/s	k_v cm/s	k_u cm/s	k_h/k_v	k_h cm/s	k_v cm/s	k_u cm/s	k_h/k_v
G-845	Frozen Core Lab Tests 2000	2000	20V-2	FV	LH	8.40E-05		2.54E-05						
G-846	Frozen Core Lab Tests 2000	2000	21H	FH	LH	7.80E-05	5.95E-04							
G-847	Frozen Core Lab Tests 2000	2000	21V	FV	LH	8.98E-05		3.39E-04						
G-848	SCL Lab 2000 Conductivity	2000	RN	LF	7.74E-04			5.76E-04						
G-849	SCL Lab 2000 Conductivity	2000	RN	LF	7.74E-04			3.44E-04						
G-850	SCL Lab 2000 Conductivity	2000	RN	LF	7.74E-04			4.92E-06						
G-851	SCL Lab 2000 Conductivity	2000	RN	LF	7.74E-04			1.25E-03						
G-852	SCL Lab 2000 Conductivity	2000	RN	LF	7.74E-04			2.03E-05						
G-853	SCL Lab 2000 Conductivity	2000	RN	LF	7.74E-04			5.10E-05						
G-854	SCL Lab 2000 Conductivity	2000	RN	LF	7.74E-04			1.88E-05						
G-855	SCL Lab 2000 Conductivity	2000	RN	LF	7.74E-04			1.51E-05						
G-856	SCL Lab 2000 Conductivity	2000	RN	LF	7.74E-04			9.53E-05						
G-857	SCL Lab 2000 Conductivity	2000	RN	LF	7.74E-04			1.23E-04						
G-858	SCL Lab 2000 Conductivity	2000	RN	LF	7.74E-04			6.26E-05						
G-859	SCL Lab 2000 Conductivity	2000	RN	LF	7.74E-04			1.74E-04						
G-860	SCL Lab 2000 Conductivity	2000	RN	LF	7.74E-04			1.20E-04						
G-861	SCL Lab 2000 Conductivity	2000	RN	LF	7.74E-04			2.03E-04						
G-862	SCL Lab 2000 Conductivity	2000	RN	LF	7.74E-04			4.58E-05						

Sample / test information							Measured				Assumed for design			
#	Program	Year	Borehole number	Sample type	Test type	Scale volume m^3	k_h cm/s	k_v cm/s	k_u cm/s	k_h/k_v	k_h cm/s	k_v cm/s	k_u cm/s	k_h/k_v
G-863	SCL Lab 2000 Conductivity	2000	RN	LF	7.74E-04			9.47E-05						
G-864	SCL Lab 2000 Conductivity	2000	RN	LF	7.74E-04			3.87E-04						
G-865	Norwest Water Balance	2001	None	CA	3.53E+03					5.00E-04	3.13E-05		16	
G-866	1995 Spiking Test	1994	P1	None	FS	8.75E+01		1.39E-05						
G-867	1995 Spiking Test	1994	P2	None	FS	1.35E+02		2.48E-05						
G-868	1995 Spiking Test	1994	P3	None	FS	1.50E+02		2.45E-05						
G-869	1995 Spiking Test	1994	P4	None	FS	5.00E+01		5.45E-06						
G-870	1995 Spiking Test	1994	P5	None	FS	8.25E+01		1.85E-05						
G-871	1995 Spiking Test	1994	P7	None	FS	8.25E+01		3.71E-05						
G-872	1995 Spiking Test	1994	P9	None	FS	7.50E+01		3.07E-05						
G-873	1995 Spiking Test	1995		None	FS	7.50E+01		1.00E-04						
G-874	1995 Spiking Test	1996		None	FS	7.50E+01		1.00E-06						
G-875	CT Bearing Capacity 2000	2000		None	FS	1.06E+01		1.20E-04						
G-876	MLSB Section Back Analysis 2001	2001		None	CB	8.27E+06	4.00E-04	2.50E-05		16				
G-877	MLSB Section Back Analysis 2001	2001		None	CB	3.67E+06	3.20E-04	2.00E-05		16				
G-878	MLSB Section Back Analysis 2001	2001		None	CB	5.31E+06	2.00E-04	1.25E-05		16				
G-879	MLSB Section Back Analysis 2001	2001		None	CB	6.91E+06	4.00E-04	4.00E-06		100				
G-880	MLSB Section Back Analysis 2001	2001		None	CB	3.82E+06	5.00E-04	3.13E-05		16				
G-881	MLSB Section Back Analysis 2001	2001		None	CB	3.92E+06	8.00E-04	5.00E-05		16				
G-882	MLSB Section Back Analysis 2001	2001		None	CB	2.72E+06	7.00E-04	4.38E-05		16				
G-883	MLSB Section Back Analysis 2001	2001		None	CB	3.08E+06	4.00E-04	2.50E-05		16				

Sample / test information							Measured				Assumed for design			
#	Program	Year	Borehole number	Sample type	Test type	Scale volume m^3	k_h cm/s	k_v cm/s	k_u cm/s	k_h/k_v	k_h cm/s	k_v cm/s	k_u cm/s	k_h/k_v
G-884	MLSB Section Back Analysis 2001	2001		None	CB	2.42E+06	2.20E-04	1.38E-05		16				
G-885	MLSB Section Back Analysis 2001	2001		None	CB	4.79E+06	4.00E-04	2.50E-05		16				
G-886	MLSB Section Back Analysis 2001	2001		None	CB	6.43E+06	5.00E-04	3.13E-05		16				
G-887	MLSB Section Back Analysis 2001	2001		None	CB	5.41E+06	4.00E-04	4.00E-04		1				
G-888	MLSB Section Back Analysis 2001	2001		None	CB	9.67E+06	8.00E-04	5.00E-05		16				
G-889	MLSB Section Back Analysis 2001	2001		None	CB	1.11E+07	7.00E-04	4.38E-05		16				
G-890	MLSB Section Back Analysis 2001	2001		None	CB	1.38E+07	3.50E-03	3.50E-05		100				
G-891	MLSB Section Back Analysis 2001	2001		None	CB	1.43E+07	2.49E-04	2.49E-05		10				
G-892	MLSB Section Back Analysis 2001	2001		None	CB	1.96E+07	1.00E-03	6.25E-05		16				
G-893	MLSB Section Back Analysis 2001	2001		None	CB	1.34E+07	7.00E-04	7.00E-04		1				
G-894	MLSB Section Back Analysis 2001	2001		None	CB	7.25E+06	1.60E-03	1.00E-04		16				
G-895	MLSB Section Back Analysis 2001	2001		None	CB	5.26E+06	2.20E-04	1.38E-05		16				
G-896	MLSB Section Back Analysis 2001	2001		None	CB	3.83E+06	2.40E-04	1.50E-05		16				
G-897	MLSB Section Back Analysis 2001	2001		None	CB	3.28E+06	2.50E-04	1.56E-05		16				
G-898	MLSB Section Back Analysis 2001	2001		None	CB	5.38E+06	1.00E-04	6.25E-06		16				
G-899	MLSB Section Back Analysis 2001	2001		None	CB	2.73E+06	4.20E-04	2.63E-05		16				
G-900	MLSB Section Back Analysis 2001	2001		None	CB	2.10E+06	1.50E-04	9.38E-06		16				
G-901	MLSB Section Back Analysis 2001	2001		None	CB	3.61E+06	1.50E-04	1.50E-06		100				

Sample / test information							Measured				Assumed for design			
#	Program	Year	Borehole number	Sample type	Test type	Scale volume m^3	k_h cm/s	k_v cm/s	k_u cm/s	k_h/k_v	k_h cm/s	k_v cm/s	k_u cm/s	k_h/k_v
G-902	MLSB Section Back Analysis 2001	2001		None	CB	7.26E+06	1.00E-04	6.25E-06		16				
G-903	MLSB Section Back Analysis 2001	2001		None	CB	1.34E+07	2.00E-04	1.25E-05		16				
G-904	MLSB Section Back Analysis 2001	2001		None	CB	1.54E+07	7.00E-04	4.38E-05		16				
G-905	MLSB Section Back Analysis 2001	2001		None	CB	1.25E+07	4.00E-04	2.50E-05		16				
G-906	MLSB Section Back Analysis 2001	2001		None	CB	1.29E+07	6.00E-04	3.75E-05		16				
G-907	MLSB Section Back Analysis 2001	2001		None	CB	1.48E+07	3.00E-04	1.88E-05		16				
G-908	MLSB Section Back Analysis 2001	2001		None	CB	1.21E+07	7.00E-04	4.38E-05		16				
G-909	SWSS Section Bank Analysis 2001	2001		None	CB	1.17E+07	8.00E-04	5.00E-05		16				
G-910	SWSS Section Bank Analysis 2001	2001		None	CB	8.53E+06	8.00E-04	5.00E-05		16				
G-911	SWSS Section Bank Analysis 2001	2001		None	CB	9.36E+06	1.00E-03	6.25E-05		16				
G-912	SWSS Section Bank Analysis 2001	2001		None	CB	1.13E+07	6.00E-04	3.75E-05		16				
G-913	Cell 16 Pump Test #2	2001	SP 00 16 22	None	FU	1.88E+03	2.09E-04							
G-914	Cell 16 Pump Test #2	2001	SP 00 16 09	None	FU	1.88E+03	9.69E-04							
G-915	Cell 16 Pump Test #2	2001	SP 00 16 18	None	FU	1.88E+03	4.77E-04							
G-916	Cell 16 Pump Test #2	2001	SP 00 16 13	None	FU	1.88E+03	4.07E-04							
G-917	Cell 16 Pump Test #2	2001	SP 00 16 8	None	FU	1.88E+03	5.33E-04							
G-918	Cell 16 Pump test #1	2001	00-16-22	None	FU	1.88E+03	3.78E-04							
G-919	Cell 16 Pump test #1	2001	00-16-22	None	FU	1.88E+03	4.16E-04							
G-920	Cell 16 Pump test #1	2001	00-16-22	None	FU	1.88E+03	3.98E-04							

Sample / test information							Measured				Assumed for design			
#	Program	Year	Borehole number	Sample type	Test type	Scale volume m^3	k_h cm/s	k_v cm/s	k_u cm/s	k_h/k_v	k_h cm/s	k_v cm/s	k_u cm/s	k_h/k_v
G-921	Cell 16 Pump test #1	2001	00-16-22	None	FU	1.88E+03	4.71E-04							
G-922	Cell 16 Pump test #1	2001	00-16-22	None	FU	1.88E+03	1.23E-03							
G-923	Cell 16 Pump test #1	2001	00-16-22	None	FU	1.88E+03	5.71E-04							
G-924	Cell 16 Pump test #1	2001	00-16-22	None	FU	1.88E+03	6.22E-04							
G-925	Cell 16 Pump test #1	2001	00-16-22	None	FU	1.88E+03	7.69E-04							
G-926	Cell 16 Pump test #1	2001	00-16-22	None	FU	1.88E+03	6.06E-04							
G-927	Cell 16 Pump test #1	2001	00-16-22	None	FU	1.88E+03	3.98E-04							
G-928	Cell 16 Pump test #1	2001	00-16-22	None	FU	1.88E+03	4.24E-04							
G-929	Cell 16 Pump test #1	2001	00-16-22	None	FU	1.88E+03	5.38E-04							
G-930	Cell 16 Pump test #1	2001	00-16-22	None	FU	1.88E+03	4.08E-04							
G-931	Cell 16 Pump test #1	2001	00-16-22	None	FU	1.88E+03	4.78E-04							
G-932	Cell 16 Pump test #1	2001	00-16-22	None	FU	1.88E+03	4.40E-04							
G-933	Cell 16 Pump test #1	2001	00-16-22	None	FU	1.88E+03	5.87E-04							
G-934	Cell 16 Pump test #1	2001	00-16-22	None	FU	1.88E+03	1.03E-03							
G-935	Cell 16 Pump test #1	2001	00-16-22	None	FU	1.88E+03	5.86E-04							
G-936	Cell 16 Pump test #1	2001	00-16-22	None	FU	1.88E+03	6.65E-04							
G-937	Cell 16 Pump test #1	2001	00-16-22	None	FU	1.88E+03	7.08E-04							
G-938	Cell 16 Pump test #1	2001	00-16-22	None	FU	1.88E+03	6.40E-04							
G-939	Model drainage flume	2000		RN	LM	3.60E-01	1.00E-03	1.00E-04		10				
G-940	Model drainage flume	2000		RN	LM	3.60E-01	2.00E-03	2.00E-04		10				
G-941	Model drainage flume	2000		RN	LM	3.60E-01	2.00E-03	2.00E-04		10				
G-942	Model drainage flume	2000		RN	LM	3.60E-01	7.00E-03	7.00E-03		1				
G-943	Model drainage flume	2000		RN	LM	3.60E-01	8.00E-04	2.00E-05		40				

Appendix D

Hydraulic conductivities of Syncrude oil sands tailings sand: calculations

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1.0 Introduction and background

This appendix documents nearly 1000 measurements of tailings sand permeability from Syncrude Canada Ltd's Mildred Lake Oil Sand Operation. It provides information to supplement and support Chapter 6 of this thesis. (In particular, it is not meant to stand alone without Chapter 6.)

The main purpose of the appendix is to provide details of the calculation and method for determining oil sands tailings sand permeability using 15 test methods. Section 2 lists existing reports that contain Syncrude oil sands tailings sands permeability data. Section 3 summarizes tailings sand geotechnical properties. Section 4 provides further information on tailings deposition at Syncrude. Section 5, the bulk of the appendix, provides details of the calculations and the results of permeability tests conducted for this study. Section 6 provides an extensive reference list. Supplement A provides additional detail on the dyke cross-section finite element back analyses.

A note to readers

This appendix uses the term "permeability" to refer to the saturated hydraulic conductivity of tailings sand as a porous media. Values are all reported in units of centimetres per second (cm/s).

Traditionally, permeability values are generally expressed to one significant digit (e.g., $k = 8x10^{-4}$ cm/s). Most practitioners would argue that permeability can only be estimated to within an order of magnitude and that even single-digit precision is usually misleading. While this assertion may be generally true, the large, relatively homogeneous deposits of tailings sand at Syncrude and the large database of values suggest that the one significant digit *is* meaningful for average values. That said, the tailings sand permeability database records values to three significant digits – this is not meant to imply accuracy or even repeatability, but conserving these extra digits in the database helps with statistical analysis and plotting. Most of the values, particularly at larger scales, range between 10^{-4} and 10^{-3} cm/s.

The tailings sand featured in this report comes from beaches and compacted cells on the Syncrude Lease 17/22 Mildred Lake Operation, deposited between 1979 and 2000 and is representative of the orebodies mined to date. There is anecdotal and visual evidence that tailings sand in Suncor Tar Island Operation beaches (at least until about 10 years ago) and in Syncrude Aurora North beaches presently is significantly coarser that typical of Mildred Lake. Though it is likely that the permeability of these other tailings sand deposits is likely higher that report in this report, it is thought that the methods described in this report to describe variability could be successful employed at these other sites, and perhaps the spatial variability is similar.

And finally, efforts have been made to increase the fines capture of tailings sand through the addition (by injection or "spiking") of fine tailings. Previous work (Cuddy et al. 1993; Klohn Leonoff Consulting Engineers 1988; McKenna et al. 1999; Thurber Engineering Ltd 1995) reveals that small amounts of mature fine tailings reduce the tailings sand permeability much more than a similar amount of naturally fines. For this reason, amended tailings sand has not been included in this study and should be treated as a separate material.

2.0 Existing tailings sand permeability data and literature

In 1996, a cursory review of available permeability for tailings sand yielded only about a dozen values. A dyke design value of $k_h = 8x10^{-4}$ cm/s with a permeability ratio of $k_h/k_v = 16$ had been chosen by Syncrude staff based on experience over 20 years, but the rationale behind this choice was never clear. The lack of a full review of existing data and the need for additional data was the main impetus for the present study.

There are numerous internal consulting reports and staff reports that provide information of tailings sand permeability. For the most part, the raw data is not available – only a final interpreted value. References are provided individually with the data, and are lumped together below: AGRA Earth and Environmental 1997; Alberta Department of the Environment. 1977; Dawson 1999; Fair and Handford 1986; Golder Associates 1996; Graham et al. 1990; Hansen and Ellis 1983; Hardy and Associates 1977; Hardy BBT Ltd 1986; HBT AGRA Limited 1992; Isaac 1980; Klohn Crippen 1997; Klohn 1979; Klohn Leonoff 1990; Klohn Leonoff Consulting Engineers 1991; Klohn-Crippen 1995; Laing et al. 1986; Lighthall 1990; McKenna 2000a; McKenna 2000b; McKenna 2000c; McKenna 2000d; McKenna 2000e; McKenna 2000f; Meier 2000; Meyer and Normore 1994; Milligan 1980; Rice 1991; Shaw et al. 1992; Skopek and McRoberts 1996; and Thurber Engineering Ltd 1990.

Papers that discuss **laboratory** methods for determining hydraulic conductivity include: Alessandro et al. 1997; Aubertin et al. 1996; Bahralolom and Heller 1991; Banton 1993; Benson et al. 1997; Bergstrom et al. 1987; Boadu 2000; Boisson et al. 1998; Dane 1980; Doll and Schneider 1995; Fredlund 2000; Gan and Fredlund 2000; Gueguen et al. 1996; Herzog and Morse 1984; Hopkins and Allen 1982; Jones 1993; Keller et al. 1988; Masch and Denny 1966; McKenna 2000f; Meyer et al. 1989; Neuzil 1994; Pandian et al. 1997; Rehfeldt et al. 1992; Richards et al. 1954; Ridlen et al. 1997; Scott 1984; Tidwell and Wilson 1997; Welty and Elsner 1997; and Wright et al. 1996.

Papers that discuss **standpipe slug tests** include: Anonymous 1996; ASTM 1991a; ASTM 1991b; Baker and Black 1983; Barker and Black 1983; Bjerg et al. 1992; Black 1978; Black 1985; Bouwer and Rice 1976; Bromley et al. 1996; Butler 1998; Butler and Healey 1998; Butler et al. 1994; Chapuis 1989; Chapuis 1998; Dawson and Istok 1991; Demir and Narasimhan 1994;

Doll and Schneider 1995; Guyonnet et al. 1993; Hinsby et al. 1992; Horseman and Harrington 1998; Hydrosolve Inc. 2000; Jones 1993; Keller et al. 1988; McKenna 2000a; McKenna 2000b; McKenna 2000c; McKenna 2000d; Moxie 1999; Rehfeldt et al. 1992; Rovey and Cherkauer 1995; Sargent et al. 1998; Shafer et al. 2000; Springer et al. 1999; and Zlotnik 1994.

Papers that discuss analysis of **pumping tests** include: Briggs and Erdmann 1998; Butler and Healey 1998; Dawson and Istok 1991; Ennis et al. 2000; Hydrosolve Inc. 2000; Jalludin and Razack 1994; Jiang 1991; Jones 1993; Mace 1993; Moench 1997; Niemann and Rovey 2000; Rushton and Howard 1982; Sargent et al. 1998; Schafmeister and Pekdeger 1993; Schulze and Cherkauer 1995; and Younger 1993

References for analysis for **flow to trenches and other subsurface drains** include: American Society of Civil Engineers 1998; Bahr and Meigs 1994; Braekke 1983; Chambers 1990; Chambers and Bahr 1992; Dunn and Mackay 1996; Evans et al. 1992; Land Improvement Contractors of Ontario 1998; Pandey et al. 1992; and Zhang et al. 1985.

References about **water table control** include: American Society of Agricultural Engineers 1992; American Society of Civil Engineers 1998; Evans et al. 1992; Land Improvement Contractors of Ontario 1998; McKenna 2000h; McKenna 2000i; McKenna 2000j; McKenna 2000l; and McKenna et al. 2001.

Use of **lysimeters** for monitoring percolation include: Allen et al. 1991; Aziz and Ferguson 2000; Bews and Barbour 2000; Dawson 1999; Ecologistics Limited and Ontario Ministry of the Environment Research and Technology Branch 1991; Faybishenko et al. 1997; Garrrrstka 1937; and Glenn et al. 1998.

Analysis of permeability values from **cone dissipation** data is described by: Gribb et al. 1998; Liu and Evett 1999; and Schnaid et al. 1997.

3.0 Tailings sand geotechnical properties

This section provides a summary of the geotechnical properties of Syncrude Mildred Lake tailings sand.

Syncrude oil sands tailings sand is loose to dense, uniform, light grey to brown, moist to wet fine natural sand, composed almost entirely of quartz. It is subangular to subrounded, weakly subhorizontally bedded with trace amounts of bitumen and clay with infrequent thin, medium grey, horizontal, clayey silt layers with a porosity averaging about 40 percent. It is often considered to be geotechnically homogeneous, but anisotropic with respect to permeability. Fluvial and deltaic lithofacies are recognized within the deposits.

During extraction of bitumen from the oil sands, the fines fraction is highly dispersed. Unlike most metal mines tailings beaches, the grain size of oil sands tailings sand (Figure 6-2) shows no measurable trends down the beach. The fines are so dispersed within the carrying fluid, that the segregation of the fines and the sand is uniform – the runoff water with fines is carried to the pond, the remaining fines are trapped with the pore-water. In that the density (and hence the porosity) has a narrow range, so does the fines content. Movement of fines or bitumen may impact the overall bulk permeability of the tailings sand. Strong interlayering of fines and sands is observed at the pond / beach interface. Much of the fines in the pore-spaces of the sand matrix are mobile and seeps from test pits and into wells are usually cloudy. This highly dispersed nature of the clay minerals (and its relatively large grain size) gives the sand relatively low permeability as compared to that predicted by Hazen (1911). In many ways, the saturated fines in the sand act as a viscous, slightly mobile slurry.

Table D-1 summarizes typical Syncrude oil sands tailings sand geotechnical properties.

Table D-1 **Typical tailings sand geotechnical properties**[1]

Property	Typical range of values
% Sand	Average = 81 (CoV =20%)
% Silt	Average = 10 (CoV =100%)
% Clay	Average = 4.4 (CoV =180%)
D_{10} (micron)	70 – 100
D_{50} (micron)	150 – 200
D_{90} (micron)	225 – 350
Coefficient of curvature, C_c	1.0 - 1.5
Coefficient of uniformity, C_u	1.7 - 2.6
Bitumen content % (m_b/m_t)	0.4 (CoV =150%)
Moisture content (m_w/m_s) %	10 – 30
Saturated moisture content (m_w/m_s) %	20 - 30
Void ratio	0.6 - 0.9
Dry density, kg/m^3	1500 - 1700
Wet density, kg/m^3	1700 - 1900
Standard Proctor dry density, kg/m^3	1600 - 1700
Optimum moisture content, kg/m^3	12 - 18
Minimum dry density (e_{max}), maximum dry density (e_{min}), kg/m^3	1275, 1590 e_{max}=1.08, e_{min}=0.67 *(relative densities well in excess of 100% are common)*
Permeability, cm/s	2×10^{-4} to 8×10^{-4}
Frictional strength	$c'=0$, $\phi'=33°$
Coefficient of consolidation, C_v	10 to 75 cm^2/min
coefficient of volume change, m_v	3×10^{-4} kPa^{-1}
Compression index, C_c	0.02 (dense), 0.06 (loose)
Swelling index, C_r	0.005

Samples of tailings were recently tested for soil-water characteristic curves (Gan and McKenna 2001). This information is important for determining unsaturated soil behaviour for water balances and water table control and is presented in Table D-2 below.

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[1] Most of this data is based a large number of tests a summary available in McKenna, G.T., Tan, S., and Ferguson, D. 1999. MFT Spiked Tailings: 1994 Field Demonstration at Syncrude's Southwest Sand Storage Facility. Internal report, Syncrude Canada Ltd, Fort McMurray.

Table D-2 Soil water characteristic curves for Syncrude tailings sand

Applied suction kPa	Volumetric water content %	Gravimetric water content %
0.01	42.1	27.9
0.5	37.8	25.1
1.0	37.4	24.8
2.5	32.2	21.4
5.0	18.8	12.5
10	13.2	8.8
20	10.5	7.0
45	6.5	4.3
80	5.1	3.4
100	4.0	2.6
200	3.6	2.4
400	3.1	2.1
1020	1.8	1.2

This curve is based on sample GT-30610, tailings beach sand from Cell1 6 beach (sand capped CT area at the CT Prototype from the ditch study area). It has similar properties and SWCC curves to other beach sands tested.

The sample tested was 90% sand, 10% silt, and 0% clay, and had a D_{50} of 180 mm, and D_{10} of 75mm. The air entry value was 2.0 kPa (36% volumetric water content).

The residual water content was 8% at 5.5 kPa. The volumetric water content at the permanent wilting point (1500kPa) was 1%.

SWCC Testing performed for Syncrude by Julian Gan of MDH Engineering, Saskatoon, SK.

An example of recent pore-water chemistry for oil sand tailings sand is presented in Table D-3 below.

Table D-3 Typical pore water chemistry in recently deposited saturated tailings sand

Constituent	Tailings pore water
$HC0_3^-$	820
$C0_3^{-2}$	60
OH^-	0
Cl^-	700
SO_4^{-2}	140
Ca^{+2}	7
Mg^{+2}	10
K^+	10
Na^+	890
Al^{+3}	0
pH	8.9
Electrical conductivity (dS/m)	2.8
Sodium adsorption ratio (SAR)	50
Exchangeable sodium potential (ESP)	40

4.0 Tailings deposition

Tailings deposition at Syncrude is described in several technical papers including: Handford et al. 1982; List and Lord 1996; List and Lord 1997; MacKinnon et al. 2000; and Nicol 1994.

The Mildred Lake Settling Basin (MLSB) is described by Dean 1980; Fair and Handford 1986; Graham et al. 1990; Handford et al. 1982; Hansen and Ellis 1983; Hardy and Associates 1977; Isaac 1991; Kampala et al. 1987; Klohn Leonoff Consulting Engineers 1991; Laing et al. 1986; Nicol 1994; and Weyer and Berzins 1986. It was built between 1978 and 1999 using centreline dyke construction methods (Klohn 1979) using cell compaction of slurried tailings sand and today is the largest ring-dyked tailings pond in the world. Heights range from 30 to 90 m, and average about 40 m. Beaches are poured by overboarding from the compacted cell back-dyke area. Typical beach slope angles range from about 1 percent near the back dyke to 0.3 to 0.5 percent downslope. Downstream slopes are terraced and have received extensive regrading. Overall slope angles range from 4H:1V to 26H:1V depending upon local foundation conditions. A series of three internal filter drains control the water table by collecting seepage into a series of headers and offtakes near the toes. Along the east side, a gravelly sand foundation drains much of the seepage water.

The Southwest Sand Storage Facility (SWSS) is described by: AGRA Earth and Environmental 1997; Klohn Leonoff 1991; Lighthall 1990; List et al. 1996; List et al. 1997; McKenna 2001; McKenna et al. 1999; and McKenna et al. 2001. It is built using upstream construction methods (Klohn 1979) with cell construction for a back dyke. Heights range from 0 to 40 m, averaging about 30 m height. Typical beach slope angles range from about 1 percent near the back dyke to 0.3 to 0.5 percent downslope. Downstream slopes are terraced and have received extensive regrading. Overall slope angles are 20H:1V and consist of 100 m berms and 100 m slopes (at 10H:1V). There are no internal filters – seepage exists under low gradients on the downstream face.

Most recently, hydraulic tailings sand capping of soft tailings such as composite tailings has become a significant design issue. These sand caps will be beached at slope angles of 0.3 to 1.0 percent and range in thickness from about 3 m to 15 m. Cell 16 at MLSB is an example of a 2 to 8 m thick sand cap and the site of much of the testing in this study.

5.0 Tailings sand permeability measurements

The state of practice for tailings sand dyke construction would involve testing a few samples of tailings in the laboratory for permeability, and choosing a suitably high value from this lab data for design. This data might be supplemented with slug tests in standpipe piezometers in test fills or each dyke instrumentation. Values would be further refined through back-analysis of seepage conditions (flows and water table locations) after a year or two of construction. The design values and the design itself evolve fairly quickly during these early years. The system is effective in the geotechnical design of tailings dykes, though fairly conservative assumptions are usually called for, and expensive remedial measures not uncommon.

The testing in this report comes after several decades of successful dyke construction and builds upon the available data in the literature – mainly from internal reports from consultants. The vast majority of the data come from field testing between 1998 and 2000 as part of the present study.

The data are organized by the type of test, arranged in approximately increasing scale, from very small sample volumes (from cone testing and in the laboratory) to kilometre-long dyke sections and summarized in Table D-4. A more thorough summary is presented in Chapter 6.

Table D-4 Summary of permeability tests by method

Test type	n	Test volume (m^3)	Generalized range k_h (cm/s)	Raw hydraulic conductive data (cm/s)				Log transform of permeability data (log cm/s)			
				Avg	σ^2	σ	COV[a] %	Avg	σ^2	σ	CoV[a] %
All data	829	10^{-4} to 10^{+7}	10^{-7} to 10^{-2}	$1.9x10^{-3}$	$3.6x10^{-5}$	$6.0x10^{-3}$	319	-3.30	0.71	0.85	26
Lab frozen core	*23*	*10^{-4}*	*10^{-5} to 10^{-3}*	*$3.5x10^{-4}$*	*$8.6x10^{-8}$*	*$2.9x10^{-4}$*	*84*	*-3.65*	*0.21*	*0.46*	*13*
Field percolation	*199*	*10^{-3}*	*10^{-3} to 10^{-2}*	*$4.5x10^{-3}$*	*$8.0x10^{-6}$*	*$2.8x10^{-3}$*	*63*	*-2.48*	*0.16*	*0.41*	*16*
Field Guelph permea-meter	*26*	*$5 x 10^{-3}$*	*10^{-4} to 10^{-2}*	*$1.2x10^{-3}$*	*$1.0x10^{-6}$*	*$1.0x10^{-3}$*	*88*	*-3.11*	*0.16*	*0.41*	*13*
Field infiltration	*30*	*10^{-2}*	*10^{-4} to 10^{-2}*	*$1.7x10^{-3}$*	*$2.8x10^{-6}$*	*$1.7x10^{-3}$*	*99*	*-3.08*	*0.39*	*0.63*	*20*
Lab reconstituted	16	10^{-3}	10^{-5} to 10^{-3}	$2.2x10^{-4}$	$9.3x10^{-8}$	$3.0x10^{-4}$	136	-3.96	0.28	0.53	13
Lab undifferent-iated	43	10^{-3}	10^{-7} to 10^{-3}	$2.7x10^{-4}$	$3.9x10^{-7}$	$6.2x10^{-4}$	232	-4.52	1.57	1.25	28
Field standpipe slug	172	10^{-2}	10^{-5} to 10^{-3}	$2.9x10^{-4}$	$2.3x10^{-7}$	$4.8x10^{-4}$	167	-3.72	0.16	0.40	11
Lab model	6	10^{-1}	10^{-3} to 10^{-2}	$2.3x10^{-3}$	$4.7x10^{-6}$	$2.2x10^{-3}$	96	-2.79	0.11	0.33	12
Field consolid-ation	10	10^{+1}	10^{-6} to 10^{-4}	$3.8x10^{-5}$	$1.4x10^{-9}$	$3.8x10^{-5}$	101	-4.69	0.33	0.57	12
Field pump	26	10^{+3}	10^{-4} to 10^{-3}	$5.8x10^{-4}$	$4.8x10^{-8}$	$2.2x10^{-4}$	38	-3.27	0.02	0.16	5
Field gradient	229	10^{+2} to 10^{+7}	10^{-4} to 10^{-2}	$2.1x10^{-3}$	$1.2x10^{-4}$	$1.1x10^{-2}$	513	-3.23	0.29	0.54	17
Field dyke back analysis	37	10^{+6} to 10^{+7}	10^{-4} to 10^{-3}	$5.8x10^{-4}$	$3.3x10^{-7}$	$5.8x10^{-4}$	99	-3.36	0.10	0.32	10
Historical dyke back analysis	7	10^{+6} to 10^{+7}	10^{-4} to 10^{-3}	$1.2x10^{-3}$	$6.0x10^{-7}$	$7.8x10^{-4}$	65	-3.11	0.24	0.49	16
All lab	82			$2.8x10^{-4}$	$2.5x10^{-7}$	$5.0x10^{-4}$	176	-4.17	1.08	1.04	25
All infiltration	*56*			*$1.4x10^{-3}$*	*$2.0x10^{-6}$*	*$1.4x10^{-3}$*	*99*	*-3.09*	*0.29*	*0.54*	*17*
All dyke back analysis	44			$6.8x10^{-4}$	$4.2x10^{-7}$	$6.5x10^{-4}$	96	-3.32	0.13	0.36	11

[a] CoV = Coefficient of variance = coefficient of variation = standard deviation / mean = σ / Avg. Coefficients of variation of log transformed distributions are sensitive to the units and base of the logarithm. In the case of the final column, base 10 logarithms are used to cover permeability data with units of cm/s.

Italicized text indicates surface beach samples (low confining stress)

5.1 Field cone tests

Some researchers use piezocone testing to estimate the horizontal consolidation coefficient (c_h) by arresting the cone penetration test in a geologic unit showing excess pore-water pressures (Gribb et al. 1998). The dissipation curve is monitored, and the 50 percent consolidation time (t_{50}) value used along with the laboratory compressibility to calculate a horizontal permeability (k_h). The reliability of this method is suspect, due to uncertainties in stresses around the cone, the size of the expansion cavity, and the stiffness / compressibility of the material (especially for collapsible tailings and hard tailings sand). These data were not included in the final database, but are included here for completeness.

The data was processed in a spreadsheet assuming a coefficient of compression for tailings sand of C_c= of 0.01 (based on tailings sand oedometer tests (McKenna et al. 1999; Thurber Engineering Ltd 1995), an initial void ratio of e_o=0.6 using the formula:

$$\boxed{k_h \cong c_h \bullet \left(0.435\frac{C_c}{\sigma_v'}\right) \bullet \frac{9.81\,\text{m/s}}{1+e_o}}$$

The coefficient of consolidation (horizontal), C_h is determined from am empirical formula based on Jones and Van Zyl that is based on mine waste (tailings) as reported by (Robertson et al. 1992) (their Figure 5):

$$\boxed{c_h(\text{cm}^2/\text{min}) = \frac{1}{t_{50}(\text{min})}}$$

The vertical effective stress (σ_v') is estimated by summing the average unit weight ($\gamma \approx 19$ kN/m^3) and subtracting the measured hydrostatic pore-water pressure at the depth of the test. The coefficient 0.435 (≈ 1/e) and is used to convert C_c to a natural logarithm and 9.81 m/s is the acceleration due to gravity used to take care of the units. The scale volume of these tests is crude estimated at 10^{-4} m^3 – the volume of a sphere 5 to 10 cm in diameter.

The tests were conducted in unspiked beach sand on the SWSS beach at various locations in Cells 34 and 48 in 1995 and involved testing beach sands that were deposited between 1991 and 1995 see ConeTec Investigations Ltd (1995) and McKenna (1999).

Results are summarized in Table D-5.

Table D-5 Results from piezocone dissipation testing

Data-base number	Test depth (m)	Time for 50% consol-idation T_{50} (sec)	Initial water table depth (m)	Coefficient of horizontal consol-idation (m^2/sec)	Estimated coefficient of com-pression C_c	Total stress (kPa)	Pore water pressure (kPa)	Coefficient of volume compress-ibility m_v (1/kPa)	Permeability (cm/s)
G-069	7.35	2.2	1.75	3.6E-04	0.035	140	55	1.1E-04	3.8E-05
G-070	1.80	10.8	-0.30	7.4E-05	0.047	32	21	8.7E-04	6.3E-05
G-071	2.40	2.1	-0.30	3.8E-05	0.047	43	26	6.1E-04	2.3E-05
G-072	3.90	79.0	-0.45	1.0E-05	0.047	70	43	3.7E-04	3.7E-06
G-073	4.40	134.0	-0.45	6.0E-06	0.047	79	48	3.2E-04	1.9E-06
G-074	4.90	99.0	-0.45	8.0E-06	0.047	88	52	2.9E-04	2.2E-06
G-075	3.50	3.5	-0.20	4.2E-06	0.047	63	36	3.8E-04	1.6E-06
G-076	1.95	2.0	-0.35	2.7E-05	0.047	35	23	8.2E-04	2.1E-05
G-077	3.60	3.6	-0.60	4.3E-06	0.047	65	41	4.3E-04	1.8E-06
G-078	1.85	1.9	-0.50	1.3E-05	0.047	33	23	1.0E-03	1.2E-05
G-079	3.85	3.9	-0.95	1.8E-06	0.047	69	47	4.6E-04	8.3E-07
G-080	4.95	5.0	1.60	1.4E-05	0.047	89	33	1.8E-04	2.4E-06
G-081	1.85	1.9	0.90	6.7E-05	0.047	33	9	4.3E-04	2.8E-05
G-082	3.85	3.9	0.50	4.9E-05	0.047	69	33	2.8E-04	1.3E-05
G-083	4.85	4.9	0.5	4.5E-06	0.047	87	43	2.3E-04	1.0E-06

The methodology of getting permeability values from cone dissipation testing is not all that solid, and the resulting values are suspect. Concerns arise over the assumptions about size of the disturbed zone, time lags in the piezometer tip, and stress changes and densification around the tip. Thus the reliability of the data is low. Given these uncertainties and the very small sample volume, and the high costs of these kinds of tests, one wonders if they are at all useful. The author will be reluctant to use the piezocone for dissipation tests (or determination of static water pressures in collapsible materials) in the future.

5.2 Laboratory reconstituted falling head tests

This method involves compaction of sand into a Proctor mould to a prescribed density and moisture content (using tailings water). Porous stones (or wire mesh and gravel which is less likely to clog with fines) are placed on the top and bottom of the sample and water is passed from the bottom to the top of the sample. The sample is often saturated under a back pressure or assumed to "field" saturate under upward flow under atmospheric pressure. Typically, a half dozen falling head tests are performed until the permeability values reach steady state.

The database contains samples tested by Thurber Engineering Ltd (1995) and at the Syncrude Operations Lab (McKenna 2000f). These latter tests were run using the following methodology: sand samples were dried to just below optimum and tailings water was added to bring the water to optimum proctor density. Samples were compacted to various densities, typically 95% of SPD in a 10-cm diameter Proctor mold. A porous stone was added to the base, and a open screen with 2-mm diameter gravel added to the top. Distilled water was run through the sample until three pore-volumes were passed using a series of falling head tests, typically with gradients of about 10. The collected effluent water was analyzed for fines content (the migrating fines from the sample) and electrical conductivity.

The 1995 tests were from samples were collected from shallow test pits from beaches at Cell 34 and 48 at the SWSS in 1995 (of sand deposited in 1994). The 2000 tests were from samples collected from shallow tests pits at the MLSB Cell 16 CT Prototype Sand Cap beach which was placed in 1998.

The data was analyzed using the formula:

$$\boxed{k = \frac{aL}{A(t_1 - t_0)} \ln\left(\frac{h_0}{h_1}\right)}$$

where L= length of sample, a= cross-sectional area of the burette, A = cross-sectional area of the sample, $t_1 - t_0$ is the time interval of the test, h_o is the initial height of the water column on the sample, and h_1 is the final height. The typical volume of these tests is 800 cm^3 or 8 x 10^{-4} m^3.

The constant-head laboratory test method is similar to that of the laboratory reconstituted falling head tests, described above, but uses a constant head rather than a falling head see (ASTM 1994). The exit flow is measured to calculate the permeability. The discharge can be tested for water chemistry, conductivity and fines content.

The follow formula is used for constant head tests:

$$\boxed{k = \frac{Q}{iA} = \frac{Q}{\frac{\Delta H}{\Delta L} A}}$$

where Q is the exit flux (cm^3/s), i is the gradient across the sample ($\Delta H/\Delta L$) and A is the cross-sectional area of the sample. The test is run until three pore-volumes are passed or until the exit flux becomes constant. The test is essentially the same as the falling head test, but benefits from having a constant gradient and avoids concerns about transient consolidation effects.

The tests are fairly inexpensive ($500-1000 each) and repeatable. However, they test a very small volume and have a wide range of variability. That the original structure and any natural layering is lost is a negative aspect of this test. The distribution of values from this test at an 800 cm^3 volume provides a basis for digital simulation of larger flow systems (such as standpipes or large infiltration tests). Table D-6 summarizes the data.

Table D-6 Results from laboratory reconstituted tests

Database number	Permeability cm/s	Program	Sample location
G-161	4.80E-04	Spiked Tailings 1993 (Syncrude 1993)	MLSB Cell 9
G-162	7.50E-06	Hardy 1986	MLSB
G-163	4.50E-04		
G-164	4.00E-03		
G-165	3.00E-07	Morgenstern 1977 (UofA)	MLSB
G-166	4.00E-07		
G-167	1.50E-06		
G-168	7.00E-06		
G-169	2.00E-06	Pollock 1988 (UofA)	MLSB
G-170	6.00E-08	Syncrude 1993	MLSB
G-171	1.00E-07		
G-172	2.90E-07		
G-173	3.00E-07		
G-174	3.58E-07		
G-175	6.00E-07		
G-099	2.63E-04	Sand Sludge 1995 (Klohn Crippen 1995)	MLSB
G-100	2.18E-04		
G-848	5.76E-04	SCL Flushing Experiment (SCL / UofA 2000)	Cell 16 CT Sand Cap Beach
G-849	3.44E-04		
G-850	4.92E-06		
G-851	1.25E-03		
G-852	2.03E-05		
G-853	5.10E-05		
G-854	1.88E-05		
G-855	1.51E-05		
G-856	9.53E-05		
G-857	1.23E-04		
G-858	6.26E-05		
G-859	1.74E-04		
G-860	1.20E-04		
G-861	2.03E-04		
G-862	4.58E-05		
G-863	9.47E-05		
G-864	3.87E-04		
G-087	1.70E-04	1994 MFT Spiking (Thurber Engineering 1995)	SWSS Cell 34
G-088	1.70E-04		

Database number	Permeability cm/s	Program	Sample location
G-089	2.00E-04		
G-090	6.00E-04		
G-091	2.00E-04		
G-092	7.00E-06		

5.3 Laboratory intact sample constant head tests

Twenty-three permeability tests were run on small intact cores cored from frozen beach tailings sand (Cell 16 CT Sand Cap). The original samples were six-inch diameter of frozen tailings sand. In the freezer, the samples were subsampled by coring to nominal 2-cm diameter and 7-cm height and loaded into a triaxial cell. The sample was thawed under 490-kPa backpressure and 500-kPa cell pressure. The backpressure was used to attempt to achieve saturation (B-value >0.98) though many values were unable to get above 0.90. A nominal 20-cm constant head was applied across the sample (to achieve gradients of about 2.5), and the exit fluxes measured. Vertical and horizontal subcores were cut from the same field cores to provide a measure of the anisotropy of the permeability.

Analysis is the same as the laboratory reconstituted sample constant head test described above. Results are presented in Table D-7. Test soil volumes were typically about 100 cm^3 or x 10^{-4} m^3.

Table D-7 Results from laboratory frozen core tests 2000

Data-base number	Sample number / location, test direction	Sample dia cm	Sample height cm	Sample mass g	Initial moisture content %	Sample volume cm^3	Wet density g/cm^3	Dry density g/cm^3	B-value	Head difference kPa	Permeability cm/s
G-825	5H	4.03	6.77	163.4	18.4	86.3	1.89	1.60	0.91	2.0	5.10E-04
G-826	5V	4.03	6.90	171.2	18.4	88.1	1.94	1.64	0.91	2.0	6.14E-04
G-827	8H	4.01	8.05	195.0	22.9	101.9	1.91	1.56	0.88	2.0	7.91E-05
G-828	8H-2	4.02	7.68	185.9	22.9	97.2	1.91	1.56	0.88	2.0	4.28E-04 5.50E-04
G-829	8V	4.03	7.94	190.3	22.9	101.0	1.88	1.53	0.97	2.0	7.07E-04 1.21E-03
G-830	8V-2	4.02	8.73	206.1	22.9	110.6	1.86	1.52	0.88	2.0	9.16E-04 1.58E-03
G-831	11H	3.99	7.69	181.1	24.3	96.2	1.88	1.51	0.90	2.5	1.44E-04
G-832	11V	3.95	6.38	129.7	24.3	78.0	1.66	1.34	0.78	2.5	1.09E-04
G-833	12H	4.02	7.16	171.9	23.7	90.9	1.89	1.53	0.94	2.5	3.57E-04
G-834	13H	4.01	6.75	164.1	24.1	85.3	1.92	1.55	0.95	2.5	2.64E-04
G-835	13V	3.99	6.54	171.7	24.1	81.8	2.10	1.69	1.00	2.5	1.81E-04
G-836	14H	4.04	6.53	158.6	21.3	83.9	1.89	1.56	0.91	2.0	1.21E-03
G-837	14V	4.00	6.87	169.1	21.3	86.3	1.96	1.62	0.65	2.0	4.38E-04
G-838	15V	3.97	7.25	168.2	26.4	89.7	1.88	1.48	1.00	2.0	2.70E-04
G-839	17H	4.04	7.27	170.8	27.1	93.0	1.84	1.45	0.78	2.0	5.67E-04
G-840	17V	4.02	6.78	155.9	27.1	86.2	1.81	1.42	0.93	2.0	6.56E-05
G-841	19H	4.00	8.18	188.5	23.7	102.6	1.84	1.48	0.73	2.0	1.99E-05 1.26E-04
G-842	19V	3.98	7.36	165.2	23.7	91.8	1.80	1.45	0.79	2.0	1.00E-03
G-843	20H	4.00	8.02	191.5	23.8	100.7	1.90	1.54	0.99	2.0	2.32E-04 3.19E-04
G-844	20V	3.96	7.94	184.6	23.8	98.0	1.88	1.52	0.95	4.0	6.64E-04 6.82E-04
G-845	20V-2	3.72	7.72	168.2	23.8	84.0	2.00	1.62	0.96	3.0	2.36E-05 2.88E-05
G-846	21H	3.73	7.12	141.8	22.6	78.0	1.82	1.48	0.99	2.0	9.14E-04
G-847	21V	3.83	7.79	165.3	22.6	89.8	1.84	1.50	0.99	2.0	4.34E-04

Note: V = Vertical permeability test (across bedding), H = Horizontal permeability test (along bedding)

Testing performed by Gerry Cyre and Steve Gamble at the University of Alberta. Frozen core sampling by Gerry Cyre.

It is interesting to note that there was no statistical difference between the horizontal and vertical permeability values, perhaps owing the minor variation in clay content between the two lab cores cut from the same field core.

This test provides more accurate testing of the field fabric and density of the sample, but involves taking frozen cores and preserving these cores. In that these tests involved field frozen cores (from frost), only the upper most layers under the least amount of stress can be tested.

Table D-8 provides results from similar tests from 1995 done on naturally frozen cores. These results are vertical tests only and are done on slightly larger samples.

Table D-8 Results from laboratory frozen core tests 1995

Database number	Vertical permeability cm/s	Sample location	Borehole number
G-093	1.50E-04	SWSS Cell 34	BH9534T-37
G-094	2.00E-04	SWSS Cell 34	BH9534T-37
G-095	4.00E-05	SWSS Beach 34	BH9534T-42
G-096	7.50E-05	SWSS Beach 34	BH9534T-43
G-097	1.50E-04	MLSB Cell 9	BH9509T-01
G-098	5.00E-04	MLSB Cell 9	BH9510T-01
These tests are from fixed piston samples of clean tailings sand from the 1994 MFT Spiking Program. Tests performed by Thurber Engineering (1995) and were tested in the laboratory under falling head conditions. Test volume =8 x 10^{-4} m^3			

5.4 Field percolation test

In 2000, a series of "coffee-can" percolation tests were done on two tailings sand beaches, mostly to test for autocorrelation distances. These crude tests involved pushing a 17-cm high, 15.4-cm diameter coffee can open on both ends 5 cm into the tailings sand beach at 1m intervals down the beach – essentially a single ring infiltrometer test. The can was filled with tailings water and the depth to the water measured at 3, 6 and 9 minutes. Two series of 100 percolation tests were run over two days, one at MLSB Cell 16 sand cap, one at the Cell 25 beach in October 2000. The water table in the sand was well below the influence of this short test (it was more than seven times the head change).

The tests provide a better indication of percolation rates than permeability and there may be errors in flow along the sides of the cans. Still, they represent a form of permeability measurement included in this test.

The tests were analyzed two ways. First, it was observed that the flow neared steady state after the second three-minute interval, and assuming general saturation of the test volume and using the following formula[2], permeability was calculated:

$$\boxed{k = \frac{q \cdot \left(1 + \frac{11}{\pi}\frac{L}{D}\right)}{2.75DH}}$$

where q is the percolation flux (cm^3/s), L = length of soil in tube (cm), D = diameter of tube (cm), H = head at base of tube (estimated as the column of water above this point, ignored suction), (cm), k is permeability (cm/s). In the case of this test, L = 5 cm, D = 15.4 cm. The initial head was about 12 cm (above ground), dropping quickly to about 8 to 11 cm then more slowly decreasing to 6 to 10 cm. With the constant geometry of these tests, the formula simplifies to:

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[2] From Hvorslev, M. 1951. Time lag and soil permeability in ground-water observations. U.S. Army Corps of Engineers, Vicksburg, Miss. Figure 13, soil in casing case (#1)

$$\boxed{k = \frac{1.14q}{H}}$$

In this case back-analyzed using Seep/W to help deal with the transient effects and unsaturated conditions. The marked bimodal percolation rate (fast at first, then slower and steady after) can only be modelled by using a higher permeability near-surface zone, probably due to both surface effects (a higher permeability zone near the beach surface, and due to disturbance by the coffee can during placement) and due to leakage along the inside *and outside* of the coffee can. The initial rate is measuring percolation in this zone, the second steady state is more indicative of the permeability of the sand outside of the disturbance. The influence of this disturbance is one reason why single-ring infiltrometer tests have fallen into disfavour.

Sensitivity analysis using Seep/W reveals that the steady state percolation rate is fairly insensitive to initial suctions and the location of the water table (provided the water table (and the "capillary rise") is well below the base of the test. The initial few minutes of the test is very sensitive to the boundary conditions and state of the sand within the coffee can – to the point where this data from this single ring percolation test cannot be relied upon or analyzed. The results are relatively insensitive to small errors in timing or errors in measurement of the water in the can, or measurement of the can or embedment depth – the results are overwhelmed by the value of the permeability.

Because thesis tests were influenced by the vertical permeability within the can and the horizontal permeability below, and because they were strongly influenced by surface effects, it was decided to consider the permeability as undifferentiated rather than vertical or horizontal.

The tested volume of sand can be calculated two ways. First, assuming an average available porosity of 0.28 (this assumes about 30 percent saturation and an initial porosity of 0.40) and measuring the volume of water added lost during the test, the test volume can be estimated. Values range from two to five litres of sand volume (2×10^{-3} to $5 \times 10^{-3} m^3$).

Second, looking at typical Seep/W analysis results, once can estimate the volume affected by examining the envelope where velocities or heads are affected. The volume affected extends about 30cm laterally from the centre of the can and about 25 cm below ground. The calculated volumes range from about 60 to 120 litres (6×10^{-2} to $12 \times 10^{-2} m^3$).

The order of magnitude difference in calculation between the two methods can be attributed to the fact that it only takes small changes in volumetric water content produce changes in heads or velocities (not all the available porosity needs to be filled). And the effects approaching the outer edge of the spheroid drop off exponentially – the "effective volume" could be estimated at about a quarter of the calculated "absolute" volume.

Furthermore, the test results tend to be dominated by soils near the percolation can. The flow has a greater probability of intersecting higher permeability zones farther from the infiltration site, and the flow is limited by conditions closer to the infiltration site.

Using judgement, and combining results from the two methods, the soil volume tested for these particular tests is estimated at approximately $10^{-3} m^3$. Results are presented in Table D-9.

Table D-9 Results from coffee can percolation tests

Data-base number	Location and distance up beach m	Depth to water at 3 min cm	Depth to water at 6 min cm	Depth to water at 9 min cm	Percolation rate 6 to 9 minute interval cm^3/s	Average head cm	Calculated permeability cm/s
G-724	Cell 16 - 1	1.5	1.6	1.8	0.21	15.3	6.83E-04
G-723	Cell 16 - 2	1.0	1.3	1.6	0.31	15.6	1.01E-03
G-722	Cell 16 - 3	3.0	3.5	4.0	0.52	13.3	1.97E-03
G-721	Cell 16 - 4	2.2	2.3	2.9	0.62	14.4	2.18E-03
G-720	Cell 16 - 5	3.4	3.7	4.0	0.31	13.2	1.19E-03
G-719	Cell 16 - 6	3.3	3.9	4.4	0.52	12.9	2.03E-03
G-718	Cell 16 - 7	1.8	2.0	2.1	0.10	15.0	3.49E-04
G-717	Cell 16 - 8	2.4	2.7	2.8	0.10	14.3	3.66E-04
G-716	Cell 16 - 9	2.6	3.0	3.4	0.41	13.8	1.51E-03
G-715	Cell 16 - 10	1.6	2.1	2.5	0.41	14.7	1.42E-03
G-714	Cell 16 - 11	3.3	3.7	3.9	0.21	13.2	7.91E-04
G-713	Cell 16 - 12	3.3	3.8	4.2	0.41	13.0	1.61E-03
G-712	Cell 16 - 13	1.5	3.1	3.6	0.52	13.7	1.91E-03
G-711	Cell 16 - 14	-	-	-	*0.72*	*13.4*	*2.73E-03*
G-710	Cell 16 - 15	2.2	3.4	4.3	0.93	13.2	3.57E-03
G-709	Cell 16 - 16	2.6	3.1	3.4	0.31	13.8	1.14E-03
G-708	Cell 16 - 17	2.1	3.7	4.3	0.62	13.0	2.41E-03
G-707	Cell 16 - 18	1.8	1.8	2.2	0.41	15.0	1.39E-03
G-706	Cell 16 - 19	2.4	3.2	3.4	0.21	13.7	7.62E-04
G-705	Cell 16 - 20	1.2	1.5	1.5	0.01	15.5	3.37E-05
G-704	Cell 16 - 21	3.1	3.9	4.5	0.62	12.8	2.45E-03
G-703	Cell 16 - 22	1.8	2.3	-	*0.47*	*15.9*	*1.48E-03*
G-702	Cell 16 - 23	2.8	2.9	3.2	0.31	14.0	1.12E-03
G-701	Cell 16 - 24	2.7	3.5	4.4	0.93	13.1	3.60E-03
G-700	Cell 16 - 25	3.4	4.7	6.0	1.35	11.7	5.83E-03
G-699	Cell 16 - 26	1.4	2.3	3.0	0.72	14.4	2.55E-03
G-698	Cell 16 - 27	1.9	2.6	3.2	0.62	14.1	2.22E-03
G-697	Cell 16 - 28	2.1	2.5	2.9	0.41	14.3	1.46E-03
G-696	Cell 16 - 29	2.7	3.7	4.8	1.14	12.8	4.50E-03
G-695	Cell 16 - 30	2.0	2.4	2.7	0.31	14.5	1.08E-03
G-694	Cell 16 - 31	2.5	3.0	3.4	0.41	13.8	1.51E-03
G-693	Cell 16 - 32	2.7	4.1	5.1	1.03	12.4	4.21E-03
G-692	Cell 16 - 33	2.9	3.9	4.6	0.72	12.8	2.87E-03
G-691	Cell 16 - 34	2.5	3.5	4.2	0.72	13.2	2.78E-03
G-690	Cell 16 - 35	3.1	4.5	5.5	1.03	12.0	4.35E-03
G-689	Cell 16 - 36	3.0	4.1	5.0	0.93	12.5	3.77E-03
G-688	Cell 16 - 37	2.5	3.4	4.0	0.62	13.3	2.36E-03
G-687	Cell 16 - 38	2.0	2.9	3.5	0.62	13.8	2.27E-03

Data-base number	Location and distance up beach m	Depth to water at 3 min cm	Depth to water at 6 min cm	Depth to water at 9 min cm	Percolation rate 6 to 9 minute interval cm^3/s	Average head cm	Calculated permeability cm/s
G-686	Cell 16 - 39	1.9	3.0	3.8	0.83	13.6	3.07E-03
G-685	Cell 16 - 40	2.4	4.4	5.1	0.72	12.3	2.98E-03
G-684	Cell 16 - 41	1.9	2.7	3.8	1.14	13.8	4.18E-03
G-683	Cell 16 - 42	2.2	2.6	3.1	0.52	14.2	1.84E-03
G-682	Cell 16 - 43	2.0	2.4	2.9	0.52	14.4	1.82E-03
G-681	Cell 16 - 44	2.0	2.3	2.8	0.52	14.5	1.81E-03
G-680	Cell 16 - 45	2.7	3.5	4.1	0.62	13.2	2.37E-03
G-679	Cell 16 - 46	2.3	3.3	4.1	0.83	13.3	3.14E-03
G-678	Cell 16 - 47	2.4	2.8	3.2	0.41	14.0	1.49E-03
G-677	Cell 16 - 48	2.1	2.9	3.5	0.62	13.8	2.27E-03
G-676	Cell 16 - 49	2.9	4.3	5.5	1.24	12.1	5.18E-03
G-675	Cell 16 - 50	3.2	4.5	5.7	1.24	11.9	5.27E-03
G-674	Cell 16 - 51	2.4	3.4	3.9	0.52	13.4	1.96E-03
G-673	Cell 16 - 52	3.2	4.4	5.1	0.72	12.3	2.98E-03
G-672	Cell 16 - 53	1.9	1.8	2.1	0.31	15.1	1.04E-03
G-671	Cell 16 - 54	3.0	3.4	3.4	0.01	13.6	3.84E-05
G-670	Cell 16 - 55	1.9	2.6	3.4	0.83	14.0	2.98E-03
G-669	Cell 16 - 56	2.0	2.8	3.4	0.62	13.9	2.25E-03
G-668	Cell 16 - 57	3.6	4.5	5.3	0.83	12.1	3.45E-03
G-667	Cell 16 - 58	3.5	4.6	5.1	0.52	12.2	2.15E-03
G-666	Cell 16 - 59	2.8	3.5	4.4	0.93	13.1	3.60E-03
G-665	Cell 16 - 60	3.3	4.5	5.8	1.35	11.9	5.73E-03
G-664	Cell 16 - 61	3.3	4.8	6.3	1.55	11.5	6.84E-03
G-663	Cell 16 - 62	2.9	4.3	5.5	1.24	12.1	5.18E-03
G-662	Cell 16 - 63	3.0	4.2	5.0	0.83	12.4	3.37E-03
G-661	Cell 16 - 64	3.5	4.9	6.1	1.24	11.5	5.45E-03
G-660	Cell 16 - 65	3.1	4.3	5.0	0.72	12.4	2.96E-03
G-659	Cell 16 - 66	2.7	3.4	3.9	0.52	13.4	1.96E-03
G-658	Cell 16 - 67	1.5	2.2	2.4	0.21	14.7	7.10E-04
G-657	Cell 16 - 68	3.1	3.9	4.4	0.52	12.9	2.03E-03
G-656	Cell 16 - 69	2.0	2.4	2.7	0.31	14.5	1.08E-03
G-655	Cell 16 - 70	2.2	3.0	3.8	0.83	13.6	3.07E-03
G-654	Cell 16 - 71	1.8	2.4	2.9	0.52	14.4	1.82E-03
G-653	Cell 16 - 72	1.5	1.8	2.0	0.21	15.1	6.92E-04
G-652	Cell 16 - 73	1.6	2.0	2.4	0.41	14.8	1.41E-03
G-651	Cell 16 - 74	1.5	1.8	1.8	0.01	15.2	3.44E-05
G-650	Cell 16 - 75	2.7	3.2	3.4	0.21	13.7	7.62E-04
G-649	Cell 16 - 76	2.6	3.0	3.6	0.62	13.7	2.29E-03
G-648	Cell 16 - 77	2.4	2.7	3.1	0.41	14.1	1.48E-03

Data-base number	Location and distance up beach m	Depth to water at 3 min cm	Depth to water at 6 min cm	Depth to water at 9 min cm	Percolation rate 6 to 9 minute interval cm^3/s	Average head cm	Calculated permeability cm/s
G-647	Cell 16 - 78	2.4	3.2	3.9	0.72	13.5	2.72E-03
G-646	Cell 16 - 79	3.0	3.8	4.5	0.72	12.9	2.84E-03
G-645	Cell 16 - 80	3.4	4.0	4.8	0.83	12.6	3.32E-03
G-644	Cell 16 - 81	2.7	3.8	4.3	0.52	13.0	2.02E-03
G-643	Cell 16 - 82	3.4	4.0	4.6	0.62	12.7	2.47E-03
G-642	Cell 16 - 83	3.0	3.9	4.4	0.52	12.9	2.03E-03
G-641	Cell 16 - 84	3.5	4.1	4.8	0.72	12.6	2.91E-03
G-640	Cell 16 - 85	3.7	4.5	5.3	0.83	12.1	3.45E-03
G-639	Cell 16 - 86	2.5	3.5	4.4	0.93	13.1	3.60E-03
G-638	Cell 16 - 87	3.4	4.4	5.2	0.83	12.2	3.42E-03
G-637	Cell 16 - 88	2.7	3.4	4.2	0.83	13.2	3.16E-03
G-636	Cell 16 - 89	3.8	4.7	5.6	0.93	11.9	3.97E-03
G-635	Cell 16 - 90	3.0	3.9	4.8	0.93	12.7	3.71E-03
G-634	Cell 16 - 91	2.7	3.6	4.7	1.14	12.9	4.47E-03
G-633	Cell 16 - 92	2.5	3.4	4.3	0.93	13.2	3.57E-03
G-632	Cell 16 - 93	1.4	2.0	2.4	0.41	14.8	1.41E-03
G-631	Cell 16 - 94	2.0	2.8	3.2	0.41	14.0	1.49E-03
G-630	Cell 16 - 95	2.3	3.0	3.4	0.41	13.8	1.51E-03
G-629	Cell 16 - 96	2.9	4.0	4.5	0.52	12.8	2.05E-03
G-628	Cell 16 - 97	1.9	2.7	3.2	0.52	14.1	1.86E-03
G-627	Cell 16 - 98	3.0	4.0	5.0	1.03	12.5	4.18E-03
G-626	Cell 16 - 99	2.5	3.3	3.9	0.63	13.4	2.37E-03
G-824	**Cell 25 - 1**	**2.1**	**3.2**	**4.3**	**1.14**	**13.3**	**4.33E-03**
G-823	Cell 25 - 2	2.9	4.6	6.3	1.76	11.6	7.68E-03
G-822	Cell 25 - 3	2.8	5.2	6.9	1.76	11.0	8.11E-03
G-821	Cell 25 - 4	3.3	4.9	6.4	1.55	11.4	6.90E-03
G-820	Cell 25 - 5	3.8	5.7	7.5	1.86	10.4	9.04E-03
G-819	Cell 25 - 6	3.8	5.7	7.3	1.66	10.5	7.96E-03
G-818	Cell 25 - 7	3.8	6.2	8.1	1.97	9.9	1.01E-02
G-817	Cell 25 - 8	3.6	5.7	7.5	1.86	10.4	9.04E-03
G-816	Cell 25 - 9	2.4	4.5	6.0	1.55	11.8	6.67E-03
G-815	Cell 25 - 10	3.2	5.8	7.8	2.07	10.2	1.02E-02
G-814	Cell 25 - 11	3.4	5.7	7.3	1.66	10.5	7.96E-03
G-813	Cell 25 - 12	3.0	4.7	6.4	1.76	11.5	7.75E-03
G-812	Cell 25 - 13	3.2	5.3	6.7	1.45	11.0	6.65E-03
G-811	Cell 25 - 14	3.2	5.2	6.7	1.55	11.1	7.09E-03
G-810	Cell 25 - 15	3.2	5.1	6.6	1.55	11.2	7.02E-03
G-809	Cell 25 - 16	2.7	4.8	6.4	1.66	11.4	7.33E-03

Data-base number	Location and distance up beach m	Depth to water at 3 min cm	Depth to water at 6 min cm	Depth to water at 9 min cm	Percolation rate 6 to 9 minute interval cm^3/s	Average head cm	Calculated permeability cm/s
G-808	Cell 25 - 17	3.3	5.6	7.5	1.97	10.5	9.49E-03
G-807	Cell 25 - 18	3.5	5.9	8.0	2.17	10.1	1.09E-02
G-806	Cell 25 - 19	3.4	5.7	7.2	1.55	10.6	7.42E-03
G-805	Cell 25 - 20	3.6	6.2	7.9	1.76	10.0	8.92E-03
G-804	Cell 25 - 21	3.5	5.4	6.9	1.55	10.9	7.22E-03
G-803	Cell 25 - 22	3.4	5.1	6.4	1.35	11.3	6.03E-03
G-802	Cell 25 - 23	3.0	4.4	5.5	1.14	12.1	4.77E-03
G-801	Cell 25 - 24	3.1	4.8	6.3	1.55	11.5	6.84E-03
G-800	Cell 25 - 25	3.9	5.7	6.6	0.93	10.9	4.33E-03
G-799	Cell 25 - 26	3.1	4.6	6.0	1.45	11.7	6.25E-03
G-798	Cell 25 - 27	2.8	4.8	6.5	1.76	11.4	7.82E-03
G-797	Cell 25 - 28	2.4	3.9	5.3	1.45	12.4	5.89E-03
G-796	Cell 25 - 29	3.6	5.9	7.8	1.97	10.2	9.77E-03
G-795	Cell 25 - 30	3.6	5.7	7.9	2.28	10.2	1.13E-02
G-794	Cell 25 - 31	3.5	5.5	6.9	1.45	10.8	6.77E-03
G-793	Cell 25 - 32	2.7	5.2	5.9	0.72	11.5	3.19E-03
G-792	Cell 25 - 33	2.8	5.1	7.0	1.97	11.0	9.06E-03
G-791	Cell 25 - 34	2.6	3.9	5.4	1.55	12.4	6.34E-03
G-790	Cell 25 - 35	2.9	4.4	5.7	1.35	12.0	5.68E-03
G-789	Cell 25 - 36	2.1	2.9	3.9	1.03	13.6	3.84E-03
G-788	Cell 25 - 37	2.4	3.8	5.4	1.66	12.4	6.74E-03
G-787	Cell 25 - 38	2.2	3.4	4.7	1.35	13.0	5.24E-03
G-786	Cell 25 - 39	2.1	3.2	4.2	1.03	13.3	3.93E-03
G-785	Cell 25 - 40	3.1	5.0	6.5	1.55	11.3	6.96E-03
G-784	Cell 25 - 41	0.4	1.4	1.8	0.41	15.4	1.36E-03
G-783	Cell 25 - 42	2.7	3.5	4.8	1.35	12.9	5.28E-03
G-782	Cell 25 - 43	3.2	5.2	7.0	1.86	10.9	8.62E-03
G-781	Cell 25 - 44	3.3	5.5	7.5	2.07	10.5	9.95E-03
G-780	Cell 25 - 45	3.4	5.0	6.5	1.55	11.3	6.96E-03
G-779	Cell 25 - 46	2.5	4.2	5.7	1.55	12.1	6.50E-03
G-778	Cell 25 - 47	3.1	4.7	6.2	1.55	11.6	6.78E-03
G-777	Cell 25 - 48	2.7	4.6	6.2	1.66	11.6	7.20E-03
G-776	Cell 25 - 49	2.9	4.7	5.9	1.24	11.7	5.36E-03
G-775	Cell 25 - 50	2.8	4.2	5.2	1.03	12.3	4.24E-03
G-774	Cell 25 - 51	2.2	3.4	4.8	1.45	12.9	5.67E-03
G-773	Cell 25 - 52	2.7	3.8	5.2	1.45	12.5	5.85E-03
G-772	Cell 25 - 53	3.0	4.0	5.2	1.24	12.4	5.05E-03
G-771	Cell 25 - 54	2.6	3.8	5.2	1.45	12.5	5.85E-03
G-770	Cell 25 - 55	2.9	4.4	5.7	1.35	12.0	5.68E-03

Data-base number	Location and distance up beach m	Depth to water at 3 min cm	Depth to water at 6 min cm	Depth to water at 9 min cm	Percolation rate 6 to 9 minute interval cm^3/s	Average head cm	Calculated permeability cm/s
G-769	Cell 25 - 56	3.8	6.0	7.5	1.55	10.3	7.64E-03
G-768	Cell 25 - 57	2.5	4.1	5.4	1.35	12.3	5.54E-03
G-767	Cell 25 - 58	3.0	4.6	6.4	1.86	11.5	8.17E-03
G-766	Cell 25 - 59	3.5	4.8	6.0	1.24	11.6	5.40E-03
G-765	Cell 25 - 60	2.6	3.8	5.2	1.45	12.5	5.85E-03
G-764	Cell 25 - 61	2.6	4.3	5.7	1.45	12.0	6.09E-03
G-763	Cell 25 - 62	3.3	5.2	6.8	1.66	11.0	7.59E-03
G-762	Cell 25 - 63	3.1	5.1	6.9	1.86	11.0	8.54E-03
G-761	Cell 25 - 64	3.6	6.1	8.4	2.38	9.8	1.23E-02
G-760	Cell 25 - 65	3.2	4.9	6.6	1.76	11.3	7.89E-03
G-759	Cell 25 - 66	2.5	3.5	4.2	0.72	13.2	2.78E-03
G-758	Cell 25 - 67	3.9	5.9	7.5	1.66	10.3	8.11E-03
G-757	Cell 25 - 68	2.6	3.4	3.9	0.52	13.4	1.96E-03
G-756	Cell 25 - 69	2.4	3.5	4.3	0.83	13.1	3.19E-03
G-755	Cell 25 - 70	2.6	4.2	5.7	1.55	12.1	6.50E-03
G-754	Cell 25 - 71	2.7	4.5	5.8	1.35	11.9	5.73E-03
G-753	Cell 25 - 72	3.7	6.4	8.5	2.17	9.6	1.15E-02
G-752	Cell 25 - 73	2.8	4.4	5.8	1.45	11.9	6.14E-03
G-751	Cell 25 - 74	3.4	5.2	7.2	2.07	10.8	9.67E-03
G-750	Cell 25 - 75	2.5	4.2	5.7	1.55	12.1	6.50E-03
G-749	Cell 25 - 76	2.4	3.3	3.8	0.52	13.5	1.94E-03
G-748	Cell 25 - 77	1.6	2.4	3.2	0.83	14.2	2.94E-03
G-747	Cell 25 - 78	2.5	3.5	4.5	1.03	13.0	4.02E-03
G-746	Cell 25 - 79	2.7	4.2	5.7	1.55	12.1	6.50E-03
G-745	Cell 25 - 80	2.9	4.7	6.4	1.76	11.5	7.75E-03
G-744	Cell 25 - 81	1.8	2.7	3.7	1.03	13.8	3.78E-03
G-743	Cell 25 - 82	2.4	4.3	5.9	1.66	11.9	7.02E-03
G-742	Cell 25 - 83	2.6	4.6	6.4	1.86	11.5	8.17E-03
G-741	Cell 25 - 84	2.9	4.7	6.3	1.66	11.5	7.26E-03
G-740	Cell 25 - 85	3.1	4.7	6.3	1.66	11.5	7.26E-03
G-739	Cell 25 - 86	3.2	4.8	6.2	1.45	11.5	6.36E-03
G-738	Cell 25 - 87	2.9	4.2	5.2	1.03	12.3	4.24E-03
G-737	Cell 25 - 88	1.4	1.7	2.2	0.52	15.1	1.73E-03
G-736	Cell 25 - 89	1.8	2.6	3.3	0.72	14.1	2.60E-03
G-735	Cell 25 - 90	2.7	4.5	5.9	1.45	11.8	6.19E-03
G-734	Cell 25 - 91	1.5	2.4	2.5	0.10	14.6	3.59E-04
G-733	Cell 25 - 92	1.5	2.4	2.9	0.52	14.4	1.82E-03
G-732	Cell 25 - 93	0.8	1.4	1.6	0.21	15.5	6.74E-04
G-731	Cell 25 - 94	4.4	6.9	8.7	1.86	9.2	1.02E-02

Data-base number	Location and distance up beach m	Depth to water at 3 min cm	Depth to water at 6 min cm	Depth to water at 9 min cm	Percolation rate 6 to 9 minute interval cm^3/s	Average head cm	Calculated permeability cm/s
G-730	Cell 25 - 95	3.6	5.2	6.7	1.55	11.1	7.09E-03
G-729	Cell 25 - 96	3.8	5.9	7.7	1.86	10.2	9.21E-03
G-728	Cell 25 - 97	2.7	3.9	5.3	1.45	12.4	5.89E-03
G-727	Cell 25 - 98	3.8	5.7	7.7	2.07	10.3	1.01E-02
G-726	Cell 25 - 99	1.7	2.6	3.5	0.93	14.0	3.37E-03
G-725	Cell 25 - 100	1.6	2.5	3.4	0.93	14.1	3.34E-03
Test date: October 18, 2000. Cloudy, +8C, slight south breeze.							
Dimensions of coffee can: Height=17.0 cm. Diameter=15.4 cm, Area = 186 cm^2. Embedment depth into sand beach = 5 cm.							
Surface description: Tailings beach sand.							
Initial phreatic surface: 80 to 150 cm below ground surface.							
Water used: Tailings seepage water, Conductivity = 3.7 dS/m							

This test was more useful as an index test in calculating the autocorrelation distance of percolation values than for permeability measurement. Considerable effort went into transient seepage analysis to attempt to firm up the analytical permeability solutions. In the end, single ring percolation tests should probably be avoided, even for order-of-magnitude estimates, unless a seal can be fully guaranteed around the inside *and* outside of the ring (not really possible without going to a bentonite system).

5.5 Field surface infiltration tests

A series of field surface infiltration tests were run by others (Golder Associates 1996; Meier 2000; Dawson 1999) These tests were run using Guelph permeameter and double-ring infiltrometers.

Results were based on steady state infiltration of water into the tailings sand surfaces (with some tests also run a few centimetres below surface). Test volumes are approximately 10^{-3} to10^{-2} m^3. Results are presented in Table D-10.

Table D-10 Results from infiltration tests

Database number	Permeability cm/s	Location / method	Company / test year
G-007	1.00E-03	SWSS Double ring infiltrometer	Golder Associates, 1996
G-008	8.80E-05		
G-009	1.87E-04		
G-010	1.04E-03		
G-011	5.09E-04		
G-012	3.92E-05		
G-013	7.50E-05	MLSB Double ring infiltrometer	
G-014	1.75E-04		
G-015	2.63E-05		
G-016	3.94E-03	Suncor, TID Double ring infiltrometer	
G-017	4.59E-03		
G-018	4.63E-03		
G-019	3.99E-03		
G-020	3.04E-03		
G-021	3.17E-03		
G-022	5.86E-04		
G-023	1.50E-03		
G-024	1.99E-03		
G-025	1.13E-03		
G-026	6.14E-04		
G-027	1.71E-03		
G-028	4.05E-03		
G-029	6.25E-03		
G-030	7.62E-04		
G-031	2.33E-04		
G-032	7.09E-04		
G-033	8.50E-04		
G-181	1.70E-04	SWSS Double ring infiltrometer	AGRA Earth and Environmental, 1996
G-223	2.07E-03	SWSS Lysimeter Guelph infiltrometer	Norwest Mine Services, 1999
G-224	1.36E-03		
G-225	6.53E-04		
G-600	1.07E-04	Cell 16 MLSB Guelph infiltrometer	University of Saskatchewan – Greg Meier, 2000
G-601	1.47E-04		
G-602	1.66E-04		
G-603	3.38E-04		
G-604	3.68E-04		
G-605	3.73E-04		
G-606	4.44E-04		

Database number	Permeability cm/s	Location / method	Company / test year
G-607	4.70E-04		
G-608	4.77E-04		
G-609	5.35E-04		
G-610	5.71E-04		
G-611	6.39E-04		
G-612	6.48E-04		
G-613	7.56E-04		
G-614	9.64E-04		
G-615	1.12E-03		
G-616	1.35E-03		
G-617	1.37E-03		
G-618	1.45E-03		
G-619	1.77E-03		
G-620	1.85E-03		
G-621	2.01E-03		
G-622	2.28E-03		
G-623	2.32E-03		
G-624	2.81E-03		
G-625	4.59E-03		

The Guelph Permeameter (Reynolds and Elrick 1987) seems to be a fast and accurate tool for measurement of surface infiltration rates.

5.6 Field falling head standpipe slug tests

Falling head tests on standpipes piezometers is one of the more common methods of determining field permeability. Methods are detailed in ASTM (1991b). In each case, a standpipe is installed with a discrete open zone at depth of known dimensions. The initial static water level is measured then raised or lowered. The changing head is measured several times as the standpipe re-equilibrates -- often a datalogger is used. The data is fitted to a curve and the permeability calculated.

For Syncrude tailings sand, measuring drawdown or rebound curves over a 10 minute period provides adequate data to determine the permeability. Most tests were conducted by adding eight litres of water to the standpipes and measuring the decline in the water level using a and electric piezometer with a datalogger set to a ten-second reading interval. The initial water level was determined with a dipping probe, the transducer lowered 2 m below the water level, allowed to stabilize for two minutes, then the water was added and the water level changes measured for 10 minutes. A few tests used a metal weighted or plastic slug to change the water level.

A few tests used an “air slug” (Anonymous 1996; Shafer et al. 2000) – where the top of the standpipe is capped, air is injected into the standpipe to depress the water level for a minute or two, then the water level re-equilibration is measured. Some tests used a small bailer to remove water from the standpipe and the measuring the rising head. Each of these results produces similar results – the choice of methods is a matter of style and convenience.

There are numerous methods of analysis for slug tests. Methods include those by Hvorslev (1951), Chapuis (1998), and Bouwer and Rice (1976). This thesis uses Hvorslev method as described below using a commercially available slug analysis (Starpoint Software 2000).
The Hvorslev (1951) method uses the following method. A basic time lag (the time for 37% (1/e) equilibration) is calculated:

$$t_{lag} = \frac{t_1 - t_2}{\ln\left[\frac{h_1}{h_0}\right] - \ln\left[\frac{h_2}{h_0}\right]}$$

where t_1 and t_2 are two time measurements, h_1 and h_2 are head measurement, and h_o is the initial static head. This timelag is usually curve fit from a head ratio (h_t/h_o) versus time graph.

A Hvorslev shape factor, which is a function of the shape of the outlet, is calculated. In the case of most of the Syncrude standpipes is given by the formula:

$$F = \frac{2\pi L}{ln\left(\frac{L}{r_s} + \sqrt{1 + \left(\frac{L}{2r_s}\right)^2}\right)}$$

where r_s is the radius of the sand pack and L is the length of the sand pack. The horizontal permeability can then be calculated as:

$$k_h = \frac{\pi r_c^{\;2}}{F \cdot t_{lag}} = \frac{r_c^{\;2}\, ln\left(\frac{L}{r_s} + \sqrt{1 + \left(\frac{L}{2r_s}\right)^2}\right)}{2L \cdot t_{lag}} \approx \frac{r_c^{\;2}\, ln\left(\frac{L}{r_s}\right)}{2L \cdot t_{lag}}$$

where r_c is the inside radius of the well casing. This formula corresponds to Case 18-G from Hvorslev (1951) for a "well-point filter in uniform soil" when the vertical permeability is assumed to be equal to the horizontal permeability ($k_h/k_v = 1$). The scale of these tests is estimated using the method from Guyonnet et al. (1993) – for the most part it is assumed to be equal to the water added (typically eight litres) during the test divided by the porosity of n=0.35.

Results using similar methods from tests between 1991 and 1996 (based on available data) are presented in are presented in Table D-11. Some of these tests used a constant head method. The field constant head standpipe test is similar in most respects to the falling head test but instead of allowing the head in the pipe to fall, it is kept at a constant elevation at the top of the pipe. This is accomplished by filling the pipe with water, starting a timer, then keeping the pipe full and adding a known amount of water. This is repeated several times and an average flow rate, q, is measured. The method is particularly simple to perform and easy to analyze. It suffers from potentially hydrofracturing the deposits and creating very high gradients in the sand pack. And if the deposit has high permeability, large amounts of water are required for the test.

Results from the 1999/2000 slug test program are presented in Table D-12. This testing was kindly and expertly performed by Gerry Cyre with keen UofA students.

Table D-11 Results from standpipe slug tests 1991-1996

Gord's database number	Permeability cm/s	Borehole number	Sample location	Program
G-037	1.02E-03	SP9651N-05	SWSS Cell 51	Syncrude SWSS Standpipes 1995/966 (Syncrude / AGRA 1996)
G-038	7.00E-04	SP9631N-11	SWSS Cell 51	
G-039	7.00E-04	SP9651N-05	SWSS Cell 51	
G-040	5.20E-04	SP9631N-11	SWSS Cell 31	
G-043	4.20E-04	SP9631G-12	SWSS Cell 31	
G-044	4.10E-04	SP9631G-12	SWSS Cell 31	
G-035	6.00E-03	SP9651G-03	SWSS Cell 51	
G-036	1.03E-03	SP9631N-11	SWSS Cell 31	
G-041	5.20E-04	SP9651N-05	SWSS Cell 51	
G-042	5.00E-04	SP9551N-07	SWSS Cell 51	
G-045	4.00E-04	SP9550N-17	SWSS Cell 50	
G-046	2.30E-04	SP9531N-06	SWSS Cell 31	
G-047	2.30E-04	SP9631N-11	SWSS Cell 31	
G-048	1.80E-04	SP9551N-02	SWSS Cell 51	
G-049	1.80E-04	SP9531N-08	SWSS Cell 31	
G-050	1.50E-04	SP9551N-06	SWSS Cell 51	
G-051	1.50E-04	SP9631N-10	SWSS Cell 31	
G-052	1.50E-04	SP9631N-11	SWSS Cell 31	
G-053	1.40E-04	SP9651N-04	SWSS Cell 51	
G-054	1.30E-04	SP9531N-07	SWSS Cell 31	
G-055	1.10E-04	SP9550N-16	SWSS Cell 50	
G-056	1.10E-04	SP9631G-12	SWSS Cell 31	
G-057	1.10E-04	SP9531N-05	SWSS Cell 31	
G-058	1.00E-04	SP9631G-12	SWSS Cell 31	
G-059	9.00E-05	SP9631N-11	SWSS Cell 31	
G-060	4.00E-05	SP9551N-05	SWSS Cell 51	
G-061	4.00E-05	SP9550N-15	SWSS Cell 50	
G-062	3.80E-05	SP9651N-01	SWSS Cell 51	
G-085	1.60E-05		MLSB	Spiked tailings 1993
G-199	5.00E-04			Oslo Spiking 1991
G-200	3.50E-05			
G-201	1.80E-04			
G-202	1.50E-04			
G-203	3.40E-05			
G-204	1.80E-04			
G-205	9.00E-04			
G-206	4.50E-04			
G-207	1.00E-03			

Table D-12 Results from standpipe slug tests 1999-2000

Standpipe number	Casing inside diameter cm	Initial water depth cm	Sand pack length cm	Sandpack diameter cm	Tip elevation masl	Permeability cm/s	Test date
00-16-05	4.6	105	58	5.2		1.06E-03	November 8, 2000
00-16-07	4.6	94	58	5.2		1.22E-04	November 8, 2000
00-16-08	4.6	99	58	5.2		3.05E-04	November 8, 2000
00-16-09	4.6	98	58	5.2		1.27E-04	November 8, 2000
00-16-10	4.6	101	58	5.2		1.45E-04	November 8, 2000
00-16-11	4.6	98	58	5.2		2.26E-04	November 8, 2000
00-16-12	4.6	101	58	5.2		1.57E-04	November 8, 2000
00-16-13	4.6	100	58	5.2		1.28E-04	November 6, 2000
00-16-14	4.6	97	58	5.2		6.60E-05	November 6, 2000
00-16-15	4.6	97	58	5.2		7.30E-05	November 6, 2000
00-16-16	4.6	93	58	5.2		4.52E-05	November 6, 2000
00-16-18	4.6	99	58	5.2		4.32E-04	November 6, 2000
00-16-19	4.6	97	58	5.2		1.90E-04	November 6, 2000
00-16-20	4.6	95	58	5.2		3.14E-04	November 6, 2000
00-16-21	4.6	87	58	5.2		5.15E-04	November 6, 2000
00-16-22	40.0	137	194	42.0		2.14E-04	July 30, 2000
00-16-26	4.6	190	128	5.2		1.62E-04	November 2, 2000
00-16-27						6.50E-05	March 1, 2000
00-16-27						1.27E-05	March 1, 2000
00-16-27	4.6	170	128	5.2		1.80E-04	November 2, 2000
00-16-28	4.6	163	128	5.2		1.78E-04	November 2, 2000
00-16-29	4.6	170	128	5.2		2.09E-04	November 2, 2000
00-16-31	4.6	203	128	5.2		2.15E-04	November 2, 2000
00-16-32						6.22E-05	March 27, 2000
00-16-32	4.6	195	128	5.2		2.35E-04	November 2, 2000
00-16-33						2.64E-05	March 27, 2000
00-16-33	4.6	221	128	5.2		2.92E-04	November 2, 2000
00-16-34	4.6	216	128	5.2		2.75E-04	November 2, 2000
00-16-35	4.6	184	128	5.2		2.40E-04	November 2, 2000
00-16-36						2.41E-04	March 27, 2000
00-16-36	4.6	190	128	5.2		2.69E-04	November 2, 2000
00-16-37						1.41E-04	March 27, 2000
00-16-37	4.6	185	128	5.2		1.99E-04	November 2, 2000

Standpipe number	Casing inside diameter cm	Initial water depth cm	Sand pack length cm	Sandpack diameter cm	Tip elevation masl	Permeability cm/s	Test date
00-16-38	4.6	196	128	5.2		1.34E-04	November 2, 2000
00-16-39	4.6	191	128	5.2		1.33E-04	November 2, 2000
00-16-40	4.6	195	128	5.2		1.16E-04	November 3, 2000
00-16-41	4.6	172	128	5.2		1.13E-04	November 3, 2000
00-16-42	4.6	176	128	5.2		1.36E-04	November 3, 2000
00-16-43	4.6	165	128	5.2		2.35E-04	November 3, 2000
00-16-44	4.6	145	128	5.2		1.60E-04	November 3, 2000
00-16-45	4.6	162	128	5.2		1.73E-04	November 3, 2000
00-16-46	4.6	169	128	5.2		1.53E-04	November 3, 2000
00-16-47	4.6	126	128	5.2		3.88E-04	November 3, 2000
00-16-48	4.6	153	128	5.2		3.27E-04	November 3, 2000
00-16-49	4.6	139	128	5.2		4.33E-04	November 3, 2000
00-16-49	4.6	477	167	20.3		2.19E-04	November 8, 2000
00-16-50	4.6	144	128	5.2		2.17E-04	November 3, 2000
00-16-50	4.6	492	167	20.3		2.45E-04	November 8, 2000
00-16-51	4.6	164	128	5.2		3.16E-04	November 3, 2000
00-16-51	4.6	267	167	20.3		4.04E-04	November 8, 2000
00-16-52	4.6	167	128	5.2		3.58E-04	November 3, 2000
00-16-52	4.6	252	187	20.3		2.80E-04	November 8, 2000
00-16-53	4.6	167	128	5.2		4.22E-04	November 3, 2000
00-16-54	4.6	165	128	5.2		3.64E-04	November 3, 2000
00-16-55	4.6	168	128	5.2		2.51E-04	November 3, 2000
00-16-56	4.6	173	128	5.2		2.64E-04	November 3, 2000
00-16-56R	4.6	175	128	5.2		2.66E-04	November 6, 2000
00-16-57	4.6	175	128	5.2		2.12E-04	November 6, 2000
00-16-58	4.6	175	128	5.2		2.20E-04	November 6, 2000
00-16-59	4.6	187	128	5.2		3.23E-04	November 6, 2000
00-16-60	4.6	171	128	5.2		1.23E-04	November 6, 2000
00-16-61	4.6	184	128	5.2		2.69E-04	November 6, 2000
00-16-62	4.6	153	128	5.2		2.38E-04	November 2, 2000
00-16-63	4.6	153	128	5.2		1.55E-04	November 2, 2000
00-16-64	4.6	193	128	5.2		2.78E-04	November 2, 2000
00-16-65	4.6	251	128	5.2		3.81E-04	November 2, 2000
00-16-67	4.6	152	128	5.2		1.08E-04	November 2, 2000
00-16-68	4.6	133	128	5.2		2.07E-04	November 2, 2000

Standpipe number	Casing inside diameter cm	Initial water depth cm	Sand pack length cm	Sandpack diameter cm	Tip elevation masl	Permeability cm/s	Test date
00-16-69	4.6	187	128	5.2		3.12E-04	November 2, 2000
00-16-70	4.6	215	128	5.2		5.22E-04	November 2, 2000
00-16-71	4.6	210	128	5.2		2.61E-04	November 2, 2000
00-16-72	4.6	161	128	5.2		1.45E-04	November 3, 2000
00-16-73	4.6	153	128	5.2		1.66E-04	November 3, 2000
00-16-74	4.6	168	128	5.2		1.37E-04	November 3, 2000
00-16-75	4.6	180	128	5.2		2.26E-04	November 3, 2000
00-16-77	4.6	149	128	5.2		3.53E-04	November 3, 2000
00-16-78	4.6	153	128	5.2		6.84E-04	November 3, 2000
00-16-79	4.6	172	128	5.2		2.52E-04	November 3, 2000
00-16-82	4.6	136	128	5.2		2.72E-04	November 3, 2000
00-16-83	4.6	153	128	5.2		1.55E-04	November 3, 2000
00-16-84	4.6	176	128	5.2		2.06E-04	November 6, 2000
00-16-85	4.6	213	128	5.2		6.64E-04	November 6, 2000
00-16-87	4.6	97	58	5.2		2.96E-04	November 3, 2000
00-16-88	4.6	129	58	5.2		9.37E-05	November 3, 2000
00-16-89	4.6	89	58	5.2		8.46E-05	November 3, 2000
00-16-90	4.6	38	58	5.2		1.01E-04	November 3, 2000
00-16-92	4.6	97	58	5.2		7.87E-05	November 3, 2000
00-16-93	4.6	140	58	5.2		8.57E-05	November 3, 2000
00-16-94	4.6	99	58	5.2		6.61E-05	November 3, 2000
00-17-02	4.8	1,557	229	20.3	329.09	6.18E-04	June 28, 2000
00-17-03	4.8	381	227	20.3	326.91	2.16E-06	June 27, 2000
00-20-07	4.7	553	189	20.3	304.60	1.34E-04	July 28, 2000
00-20-07			189	20.3	304.60	1.32E-04	July 31, 2000
00-20-08	4.7	1,975	223	20.3	304.63	5.68E-04	July 28, 2000
00-22-02	4.7		229	20.3	300.15	1.36E-04	July 28, 2000
00-22-05	4.7	1,686	725	20.3	306.50	6.41E-05	July 28, 2000
00-22-05			725	20.3	306.50	6.41E-05	August 1, 2000
00-22-06	4.7	1,240	1,481	20.3	313.86	5.76E-06	July 27, 2000
81-03-01	4.0				306.81	2.20E-04	July 4, 2000
81-03-04	4.0				310.62	4.77E-04	July 4, 2000
88-21-06	3.5	1,443	336	20.3	305.47	3.79E-05	July 27, 2000
92-11-04	5.0		120	20.3	325.33	9.28E-04	July 4, 2000
94-02-01	5.0	2,033	377	20.3	316.10	2.34E-04	June 29, 2000

Standpipe number	Casing inside diameter cm	Initial water depth cm	Sand pack length cm	Sandpack diameter cm	Tip elevation masl	Permeability cm/s	Test date
94-03-01	5.0	2,162	361	20.3	316.48	4.14E-04	July 4, 2000
94-03-01	5.0	2,162			316.48	6.93E-05	July 4, 2000
94-03-01	5.0		361	20.3	316.48	4.14E-04	July 4, 2000
94-04-01	5.0	1,893	322	20.3		6.94E-05	June 29, 2000
94-07-01	5.2	1,087	363	20.3	325.63	2.64E-04	June 28, 2000
95-31-06	5.0	331	274	20.3	353.17	2.26E-04	July 28, 2000
95-31-08	4.7	533	214	20.3	362.16	2.01E-04	July 28, 2000
95-50-15	4.7	114	183	20.3		4.73E-05	July 28, 2000
95-50-15			183	20.3		4.73E-05	August 3, 2000
95-50-16	4.7	264	244	20.3	358.05	2.77E-04	July 28, 2000
95-51-05	4.7	231	244	20.3	353.13	1.31E-04	July 28, 2000
95-51-06	4.7	263	214	20.3	354.03	1.68E-04	July 28, 2000
96-16-03	4.8	1,792	315	20.3	324.86	2.26E-04	June 27, 2000
96-16-03	4.8	1,792	315	20.3	324.86	5.28E-04	July 28, 2000
96-16-06	4.8	1,492	224	20.3	319.93	5.73E-04	June 27, 2000
96-16-07	4.8	1,632	188	20.3	321.94	9.27E-04	June 27, 2000
96-30-04	4.8	1,614	243	20.3	301.50	2.29E-04	June 29, 2000
96-30-05	4.8	2,114	199	20.3	312.55	3.29E-04	June 29, 2000
96-31-10	5.0	401	335	6.0	363.30	8.83E-05	August 29, 1996
96-31-11	5.0	255	137	19.0	365.30	7.70E-05	August 29, 1996
96-31-11	5.0	255	137	19.0	365.30	9.98E-05	August 29, 1996
96-31-11	5.0	342	284	6.0	365.30	1.66E-04	August 29, 1996
96-31-11	4.7	140	140	20.3	365.30	2.52E-04	July 28, 2000
96-51-01	4.7	86	230	20.3	356.40	8.84E-04	July 28, 2000
96-51-03	4.7	313	360	20.3	367.10	1.32E-04	July 28, 2000
96-51-04	4.7	135	209	20.3	366.76	3.62E-04	July 28, 2000
96-51-05	4.7	317	135	20.3	370.00	2.84E-04	July 28, 2000
97-16-19	4.6	573	213	20.3	320.87	5.41E-05	November 6, 2000
97-16-20	4.6	533	198	20.3	320.91	1.00E-04	November 6, 2000
98-04-01	4.8	1,141	360	20.3	321.74	4.24E-04	June 29, 2000
98-08-01	4.8	791	487	20.3	321.47	2.64E-04	June 28, 2000
98-16-10	4.8	1,799	325	20.3	325.21	2.41E-04	June 27, 2000
98-16-11	4.8	975	336	20.3	325.42	6.10E-04	June 27, 2000
98-16-11	4.8	969	336	20.3	325.42	7.41E-04	June 30, 2000
98-16-11	4.8	969	336	20.3	325.42	1.40E-03	June 30, 2000

Standpipe number	Casing inside diameter cm	Initial water depth cm	Sand pack length cm	Sandpack diameter cm	Tip elevation masl	Permeability cm/s	Test date
98-16-11	4.8	969	336	20.3	325.42	1.60E-03	June 30, 2000
98-16-11	4.8	975	336	20.3	325.42	1.56E-03	July 4, 2000
98-16-11	4.8	975	336	20.3	325.42	1.63E-03	July 4, 2000
98-16-11	4.8	975	336	20.3	325.42	8.90E-04	July 4, 2000
98-16-11	4.8	975	336	20.3	325.42	6.93E-04	July 4, 2000
98-17-02	4.8	1,676	358	20.3	323.66	2.56E-04	June 27, 2000
98-17-05	4.8	663	330	20.3	327.10	5.04E-04	June 27, 2000
98-18-02	4.8	2,707	336	20.3		4.93E-04	June 28, 2000
98-49-01	4.7	497	375	20.3	369.30	6.55E-05	July 28, 2000
98-49-01			375	20.3	369.30	6.55E-05	August 8, 2000
98-49-02	4.7	126	533	20.3	363.12	5.86E-05	July 28, 2000
98-49-03	4.7	496	392	20.3	361.25	1.65E-04	July 28, 2000
98-49-03			392	20.3	361.25	1.65E-04	August 5, 2000
98-49-04	4.7	240	335	20.3	359.17	3.71E-04	July 28, 2000
99-16-24						1.39E-04	September 3, 1999
99-16-25					331.31	9.97E-05	September 3, 1999
99-16-26					334.20	1.13E-04	September 3, 1999
99-16-26					334.20	1.06E-04	September 3, 1999
99-16-26					334.20	1.08E-04	October 10, 1999
99-16-27					331.18	9.97E-05	September 3, 1999
99-16-27					331.18	1.05E-04	October 10, 1999
99-16-30					330.82	2.05E-04	September 3, 1999
99-16-31					330.05	1.20E-04	September 3, 1999
99-16-33					333.55	4.99E-05	September 3, 1999
99-16-33					333.55	4.63E-05	October 10, 1999
99-16-34					330.68	1.92E-04	September 3, 1999
99-16-34					330.68	1.44E-04	October 10, 1999
99-16-35					329.17	1.25E-05	October 10, 1999
99-16-36					333.44	6.53E-05	October 10, 1999
99-16-39					333.09	7.70E-05	October 10, 1999
99-16-42						4.21E-05	October 10, 1999
99-16-49	5.0		167	20.3	326.55	1.86E-04	July 4, 2000
99-16-50	5.0		167	20.3	329.91	2.93E-04	July 4, 2000
99-48-01	4.7	356	335	20.3	362.71	1.42E-04	July 28, 2000
99-48-02	4.7	499	371	20.3	360.07	1.11E-04	July 28, 2000

Standpipe number	Casing inside diameter cm	Initial water depth cm	Sand pack length cm	Sandpack diameter cm	Tip elevation masl	Permeability cm/s	Test date
99-48-03	4.7	438	335	20.3	358.68	1.74E-04	July 28, 2000
99-48-04	4.7	1,059	386	20.3	359.57	1.71E-04	July 28, 2000

As discussed in Chapter 6, this set of slug test data provides one of the better datasets in the study because of its size, simplicity of testing and analysis, the variety of depths and locations tested, and the general uniformity of the completion zones. Some additional tests were run on other natural foundation materials that are not included in this present database.

5.7 Laboratory model tests

Two types of laboratory model tests were performed – the first was a 6-m long, 0.3-m wide flume with drains simulating ditches at either end. The second was a 1:100 scale model dam cross-section of the SWSS at a overall 20H:1V. Sands were from Cell 25 and back analyzed using Seep/W. Results are presented in Table D-13.

Table D-13 Results from model tests

Database number	Program test number	Scale volume m^3	Horizontal permeability cm/s	Vertical permeability cm/s	k_H/k_V ratio
G-425		0.40	8.00E-04	8.00E-04	1
G-939	Trial #1	0.36	1.00E-03	1.00E-04	10
G-940	Trial #2	0.36	2.00E-03	2.00E-04	10
G-941	Trial #3	0.36	2.00E-03	2.00E-04	10
G-942	Trial #4	0.36	7.00E-03	7.00E-03	1

These tests were more useful for determining and observing seepage flow mechanisms and performing trial salt balances than for determining permeabilities. The high permeabilities recorded are thought to be due to the low stress conditions – similar to those for shallow beach sands.

5.8 Field tailings sand cell construction dissipation tests

This method involves measuring pore-water pressure dissipation of sand quickly loaded with a second during the 1994 MFT Spiked Tailings program (McKenna, 1999). The data comes from pore-water pressure dissipation curves from August 19 to 28, 1994. A vibrating-wire piezometer tip was located within initial lift The situation can be imperfectly modelled by making some simplifying assumptions including the pore-water pressure increases are due to loading of tailings sand, the permeability is constant and isotropic, the dissipation can be modelled as one-way vertical drainage.

Full dissipation of excess pore-water pressures occurred in about three days. The coefficient of volume change, $m_v=3 \times 10^{-4}$ kPa^{-1}, is based on laboratory consolidation tests. The result of the calculations is a coefficient of consolidation (c_v) of 5×10^{-5} m/s and a permeability of about $k=10^{-5}$ cm/s (plus or minus about one order of magnitude). The lift was about 5m thick. The characteristic scale volume is estimated at 10 m^3. Results are listed in Table D-14.

Table D-14 Results from field dissipation tests

Tip number	Tip elevation masl	Tip depth below ground m	Approx time for 95% dissipation (t_{90}, hours)	Coefficient of consolidation c_v, cm^2/min	Permeability cm/s
P1	363.5	3.5	72	28	1.4E-05
P2	364.1	5.4	96	51	2.5E-05
P3	363.5	6.0	120	50	2.5E-05
P4	367.5	2.0	60	11	5.5E-06
P5	366.2	3.3	48	38	1.9E-05
P7	366.2	3.3	24	76	3.7E-05
P9	366.5	3.0	24	63	3.1E-05

Vagaries in the boundary conditions and the analysis cast some doubt on the permeabilities derived from this test.

5.9 Field pump test

There is a lack of well-pumping data for oil sands tailings sand, mostly because this kind of dewatering has not been needed to date, partly because the fine sand tends to flow into the well, clogging the intake and pump.

In 2000, a pumping well and 16 observation wells were installed at the composite tailings prototype sand cap – Cell 16 at the north end of MLSB. The well was installed using a small backhoe because the site was untrafficable to larger equipment or drill rigs. Four wells were installed in each compass direction to attempt to measure spatial variation over the 20 m diameter area of the test. (Typically just a couple of observations wells would be employed, but the test was designed to provide a more statistical result). Two pump tests were run, the first during the summer, the second in the fall. The first test did not capture enough data for a transient analysis, and only a steady state analysis was conducted. The second test used dataloggers to capture more data and the wells closest the pumping well were analyzed in some detail. Both tests were successful and the results reported here.

The first pump test used steady state (approximately equilibrium) drawdown values based on the Theim formula (Ferris, 1962):

$$\boxed{k = \frac{T}{b} = \frac{Q\ln\left(\frac{r_2}{r_1}\right)}{2\pi b(s_1 - s_2)}}$$

where T is the transmissivity of the unconfined aquifer, b is the aquifer thickness, Q is the constant pumping rate, r_2 and r_1 are the distances from the pumped well to the second and first observation wells, and s_1 and s_2 are the drawdown each observation well.

The assumptions for use of this formula are fairly restrictive in theory, but have been found to be widely applicable. Two departures in this test were the fact that the observation and pumping wells were only partially penetrating (2-m long well set in a 6-m thick unconfined aquifer) and there is likely some anisotropy in the permeability. These factors are likely partially offsetting , and the aquifer thickness was assumed to be the same as the well penetration (1.99m). This correction gives the same range of permeabilities as the second trial (with a more rigorous analysis) and the anisotropy of the permeability is thought to reduce the amount of flow from deeper in the aquifer. So while the measured permeability is somewhat sensitive to this assumption (but not the order of magnitude), the range of variation is thought to be less affected (based on a sensitivity analysis using different aquifer thicknesses.

Both tests also revealed that the measured storativity of the sands in the pump test were very small (0.01). It is thought that this is due to the very low flow rates employed (the aquifer was not all that stressed) and due to the fact that the water table was near surface to start with and was only lowered 0.2 to 0.6m by the pumping test. This has important implication for any future dewatering of shallow tailings sand – it is often not enough to lower the water table – significant desaturation (needed to reduce susceptibility to liquefaction and improve root aeration) may require greater lowering of water tables and tracking of soil moisture rather than just pressures.

The second test (Ennis, 2000;Karvin, 2000; Dawson, 2000) used Jacob's transient analysis (Ferris, 1962):

$$\boxed{k = \frac{T}{b} = \frac{2.3Q\log\left(\frac{t_2}{t_1}\right)}{4\pi b(s_2 - s_1)}}$$

In this case, the radius does not come into effect if t is reasonably large and r is reasonably small. Usually the t_2 / t_1 ratio is selected to be a factor of 10 for ease of computation (and the change in drawdown (s_2-s_1) is measured over "one log cycle.".

Both tests ran at 0.5 litres per minute (very low flow) over about 6 days, and had a reach of about 20 m (The theoretical reach is where the extrapolated drawdown reaches zero, which for this test is about 40 to 100 m, but the water table lowering in this region is near zero.). Steady state conditions were reached in about four days. Drawdowns ranged from about 1 m near the pumping well, to 0.5 m about 10 m away. The test scale is estimated at about 20 m diameter, or about 2000 m^3 based on the effective reach discussed above. Results are provided in Table D-15 below.

Table D-15 Results from field pump tests

Database number	Permeability cm/s	Borehole number	Program
G-913	2.09E-04	SP 00 16 22	Cell 16 Pump Test #2 Norwest Mine Services Jacob's transient analysis 2001
G-914	9.69E-04	SP 00 16 09	
G-915	4.77E-04	SP 00 16 18	
G-916	4.07E-04	SP 00 16 13	
G-917	5.33E-04	SP 00 16 08	
G-918	3.78E-04	00-16-22 and various pairings	Cell 16 Pump test #1 2000 Syncrude / UofA Steady state analysis
G-919	4.16E-04		
G-920	3.98E-04		
G-921	4.71E-04		
G-922	1.23E-03		
G-923	5.71E-04		
G-924	6.22E-04		
G-925	7.69E-04		
G-926	6.06E-04		
G-927	3.98E-04		
G-928	4.24E-04		
G-929	5.38E-04		
G-930	4.08E-04		
G-931	4.78E-04		
G-932	4.40E-04		
G-933	5.87E-04		
G-934	1.03E-03		
G-935	5.86E-04		
G-936	6.65E-04		
G-937	7.08E-04		
G-938	6.40E-04		

The main feature of this test is that it is the only successful one in Syncrude tailings sand and provided reasonable values. The filter cloth around the pumping well was successful in blocking sand migration yet did not measurably clog.

The test is so small (only a 2m deep well) that it has limited usefulness in practice. It does highlight the need to check assumptions, especially of storativity, for very near surface dewatering – a feature of shallow water table tests. One must also be careful to consider the effects of evapotranspiration or percolation during the test – it may not always be possible to ignore these effects in shallow water table tests.

The half order of magnitude of permeability tests produced by this test indicates both minor errors in the method and measurements, and the range in spatial variability over the area of the test. The low range in variability seems to fit the idea that the range decreases with larger test sizes. Normally one would have just a couple observation wells, so this indicates that this method is repeatable only to within about half an order of magnitude for the particular test. This is quite a narrow range (relative to general permeability measurements) but if one is counting on certain minimum or maximum outflows from pumping wells, the range is considerable and must be considered in any commercial scheme. Once again, testing at the same scale as planned commercial usage is a good idea. Pump test results in general should indicate an accuracy of about half an order of magnitude for similar materials (rather than the two decimal places often presented).

5.10 Field gradient between standpipes measurements

At MLSB, there are about 30 instrumented cross-sections with pneumatic and standpipe piezometers installed. These piezometers provide a measure of piezometric heads at various locations in the cross-sections. Additionally, there are filter drains within the structure that provide two crucial pieces of information – they are sites of zero excess pressure (a known head at a known location) and more importantly, they provide a direct measure of the flux through the section. Known fluxes and known head differences between pairs of standpipes and between standpipes and drains allows an estimate of the average permeability between these locations. Various pairs of standpipes can be analyzed, and average permeability across these known distances can be calculated.

The method has a some limitations. It assumes the fluxes at all locations in the section are the same – not exactly true as some sections are considerably influenced by a distributed percolation that is not considered by the analysis. Second, the piezometric head at depth, rather than the location of the water table, is measured. In most cases, the potentiometric lines are nearly vertical, and the difference between the piezometric head and distance to water table is relatively small and the errors in calculated permeability are small anyway.

The horizontal permeability is calculated from first principles, where i is the hydraulic gradient, A is the unit cross-sectional area of flow, H_1 and H_2 are the measured heads at two locations separated by a distance L. Q is the discharge flux. This equation is numerically equivalent to the Dupuit-Forchheimer equation.

$$\boxed{k_h = \frac{Q}{iA} = \frac{Q}{\left(\frac{H_2 - H_1}{L}\right) - \left(\frac{H_2 + H_1}{2}\right)} = \frac{2LQ}{{H_1}^2 - {H_2}^2}}$$

The characteristic length of the test is chosen as the distance, L, between the measurement points. The characteristic volume is calculated by multiplying the length, L, by the vertical height (an averaged H, and the lateral width estimated on the basis of dispersion to be about 10 percent of the length (Schulze-Makuch et al., 1999). Results are presented in Table D-16 below.

Table D-16 Results from field gradient analyses

Cross-section	Up-stream tip	Up-stream head masl	Down-stream tip	Down-stream head masl	Distance between points m	Flow boundary base elevation masl	Gradient	Seepage flux m^3/m/day	Average flow area m^2/m	Permeability cm/s
08+60E	SP99-21-01	322.13	SP91-29-01	307.04	245	302	0.062	0.480	12.6	7.17E-04
18+00E	SP99-28-01	321.64	PN8328-04	311.80	128	301	0.077	0.029	15.7	2.78E-05
18+00E	SP99-28-01	321.64	PN83-28-03	308.84	167	301	0.077	0.029	14.2	3.08E-05
18+00E	SP99-28-01	321.64	SP8328-01	309.03	230	301	0.055	0.029	14.3	4.27E-05
18+00E	PN83-2804	311.80	PN83-28-03	308.84	39	301	0.076	0.029	9.3	4.75E-05
18+00E	PN83-28-04	311.80	SP83-28-01	309.03	102	301	0.027	0.029	9.4	1.31E-04
18+00E	PN83-28-03	308.84	SP83-28-01	309.03	63	301	-0.003	0.029	7.9	1.40E-03
24+00E	PN86-27-01	314.39	PN86-27-02	312.05	19	300	0.123	0.041	13.2	2.91E-05
24+00E	PN86-27-01	314.39	SP94-27-01	313.25	50	300	0.023	0.041	13.8	1.51E-04
24+00E	PN86-27-01	314.39	SP81-27-15	308.60	117	300	0.049	0.041	11.5	8.34E-05
24+00E	PN86-27-02	312.05	SP94-27-01	313.25	31	300	-0.039	0.041	12.7	9.69E-05
24+00E	PN86-27-02	312.05	SP81-27-15	308.60	98	300	0.035	0.041	10.3	1.31E-04
24+00E	SP94-27-01	313.25	SP81-27-15	308.60	67	300	0.069	0.041	10.9	6.26E-05
95+00E	SP98-17-02	337.38	PN91-17-01	338.22	30	316	-0.028	0.450	21.8	8.53E-04
95+00E	SP98-17-02	337.38	SP98-17-03	332.27	810	316	0.006	0.450	18.8	4.39E-03
95+00E	PN91-17-01	338.22	SP98-17-03	332.27	780	316	0.008	0.450	19.2	3.55E-03
43+00 W	PN85-07-02	328.32	B-21 filter	323.00	43	316	0.124	0.436	9.7	4.22E-04
43+00 W	B-21 filter	323.00	SP90-07-09	322.99	118	317	0.000	0.064	6.0	1.46E-01
43+00 W	B-21 filter	323.00	SP91-07-03	322.68	247	319	0.001	0.064	3.8	1.49E-02
43+00 W	SP90-07-09	322.99	SP91-07-03	322.68	129	321	0.002	0.064	1.8	1.68E-02
37+00 W	SP98-06-01	342.41	PN88-06-54	336.53	272	313	0.022	0.622	26.5	1.26E-03
37+00 W	SP98-06-01	336.53	PN85-06-01	332.01	350	313	0.013	0.622	21.3	2.62E-03

Cross-section	Up-stream tip	Up-stream head masl	Down-stream tip	Down-stream head masl	Distance between points m	Flow boundary base elevation masl	Gradient	Seepage flux $m^3/m/day$	Average flow area m^2/m	Permeability cm/s
37+00 W	SP98-06-01	336.53	PN87-06-05	325.16	404	313	0.028	0.622	17.8	1.43E-03
37+00 W	SP98-06-01	336.53	B-22 filter	323.00	436	313	0.031	0.622	16.8	1.38E-03
37+00 W	PN88-06-54	336.53	PN85-06-01	332.01	78	313	0.058	0.622	21.3	5.84E-04
37+00 W	PN88-06-54	336.53	PN87-06-05	325.16	132	313	0.086	0.622	17.8	4.68E-04
37+00 W	PN88-06-54	336.53	B-22 filter	323.00	164	313	0.082	0.622	16.8	5.20E-04
37+00 W	PN85-06-01	332.01	PN87-06-05	325.16	54	313	0.127	0.622	15.6	3.64E-04
37+00 W	PN85-06-01	332.01	B-22 filter	323.00	86	313	0.105	0.622	14.5	4.74E-04
37+00 W	PN87-06-05	325.16	B-22 filter	323.00	32	313	0.068	0.622	11.1	9.63E-04
37+00 W	B-22 filter	323.00	PN85-06-03	320.65	14	316	0.168	0.044	5.8	5.21E-05
37+00 W	B-22 filter	323.00	SP90-06-04	320.69	101	316	0.023	0.044	5.8	3.81E-04
37+00 W	PN85-06-03	320.65	SP90-06-04	320.69	87	316	0.000	0.044	4.7	2.37E-02
31+00 W	PN85-05-01	329.26	PN85-05-02	326.16	50	315	0.062	0.621	12.7	9.12E-04
31+00 W	PN85-05-01	329.26	B-22 filter	316.00	94	315	0.141	0.621	7.6	6.67E-04
31+00 W	PN85-05-02	329.26	B-22 filter	316.00	44	315	0.301	0.621	7.6	3.12E-04
31+00 W	B-22 filter	316.00	PN85-05-03	320.96	54	316	-0.092	0.049	2.5	2.51E-04
26+00 W	SP98-04-01	336.72	PN91-04-05	336.82	55	306	-0.002	0.390	30.8	8.07E-03
26+00 W	SP98-04-01	336.72	PN86-04-05	331.61	262	309	0.020	0.390	25.2	9.20E-04
26+00 W	SP98-04-01	336.72	PN91-04-04	328.57	286	309	0.028	0.390	23.6	6.70E-04
26+00 W	SP98-04-01	336.72	B-02 Filter	320.00	430	314	0.039	0.390	14.4	8.08E-04
26+00 W	PN91-04-05	336.82	PN86-04-05	331.61	207	306	0.025	0.390	28.2	6.36E-04
26+00 W	PN91-04-05	336.82	PN91-04-04	328.57	231	309	0.036	0.390	23.7	5.33E-04
26+00 W	PN91-04-05	336.82	B-02 Filter	320.00	375	314	0.045	0.390	14.4	6.98E-04
26+00	PN86-	331.61	PN91-	328.57	24	316	0.127	0.390	14.1	2.53E-04

Cross-section	Up-stream tip	Up-stream head masl	Down-stream tip	Down-stream head masl	Distance between points m	Flow boundary base elevation masl	Gradient	Seepage flux m^3/m/day	Average flow area m^2/m	Permeability cm/s
W	04-05		04-04							
26+00 W	PN86-04-05	331.61	B-02 Filter	320.00	168	316	0.069	0.390	9.8	6.66E-04
26+00 W	PN91-04-04	328.57	B-02 Filter	320.00	144	316	0.060	0.390	8.3	9.15E-04
26+00 W	B-02 Filter	320.00	PN86-04-07	319.36	132	317	0.005	0.025	2.7	2.25E-03
26+00 W	B-02 Filter	320.00	SP90-04-23	322.89	138	317	-0.021	0.025	4.4	3.13E-04
26+00 W	SP90-04-22	321.66	SP90-04-08	320.20	142	320	0.010	0.025	0.9	3.05E-03
10+00w	SP99-02-01	323.63	PN86-02-01	320.99	62	304	0.043	0.484	18.3	7.19E-04
10+00w	SP99-02-01	323.63	SP94-02-01	317.74	125	304	0.047	0.484	16.7	7.13E-04
10+00w	SP99-02-01	323.63	PN93-02-01	313.76	129	304	0.077	0.484	14.7	4.98E-04
10+00w	SP99-02-01	323.63	SP94-02-02	309.00	179	304	0.082	0.484	12.3	5.57E-04
10+00w	PN86-02-01	320.99	SP94-02-01	317.74	63	304	0.052	0.484	15.4	7.07E-04
10+00w	PN86-02-01	320.99	PN93-02-01	313.76	67	304	0.108	0.484	13.4	3.88E-04
10+00w	PN86-02-01	320.99	SP94-02-02	309.00	117	304	0.102	0.484	11.0	4.97E-04
10+00w	SP94-02-01	317.74	PN93-02-01	313.76	4	304	0.995	0.484	11.8	4.79E-05
10+00w	SP94-02-01	317.74	SP94-02-02	309.00	54	304	0.162	0.484	9.4	3.69E-04
10+00w	PN93-02-01	313.76	SP94-02-02	309.00	50	304	0.095	0.484	7.4	7.97E-04
04+00 W	SP99-01-01	322.59	PN86-01-01	320.52	27	300	0.077	0.484	21.6	3.39E-04
04+00 W	SP99-01-01	322.59	PN86-01-03	315.54	91	300	0.077	0.484	19.1	3.79E-04
04+00 W	SP99-01-01	322.59	SP94-01-01	310.93	139	300	0.084	0.484	16.8	3.98E-04
04+00 W	PN86-01-01	320.52	PN86-01-03	315.54	64	300	0.078	0.484	18.0	3.99E-04
04+00 W	PN86-01-01	320.52	SP94-01-01	310.93	112	300	0.086	0.484	15.7	4.16E-04
04+00 W	PN86-01-03	315.54	SP94-01-01	310.93	48	300	0.096	0.484	13.2	4.41E-04
40+00E	SP99-25-01	323.51	PN91-25-01	323.17	10	311	0.034	0.303	12.3	8.36E-04

Cross-section	Up-stream tip	Up-stream head masl	Down-stream tip	Down-stream head masl	Distance between points m	Flow boundary base elevation masl	Gradient	Seepage flux $m^3/m/day$	Average flow area m^2/m	Permeability cm/s
40+00E	SP99-25-01	323.51	PN86-25-01	319.30	77	311	0.055	0.303	10.4	6.17E-04
40+00E	SP99-25-01	323.51	B12-filter	314.00	134	311	0.071	0.303	7.8	6.37E-04
40+00E	PN91-25-01	323.17	PN86-25-01	319.30	67	311	0.058	0.303	10.2	5.93E-04
40+00E	PN91-25-01	323.17	B12-filter	314.00	124	311	0.074	0.303	7.6	6.25E-04
40+00E	PN86-25-01	319.30	B12-filter	314.00	57	311	0.093	0.303	5.7	6.68E-04
53+00E	SP99-23-01	322.30	PN86-23-09	317.90	78	304	0.056	0.460	16.1	5.86E-04
53+00E	SP99-23-01	322.30	PN85-23-07	312.35	230	304	0.043	0.460	13.3	9.24E-04
53+00E	SP99-23-01	322.30	PN85-23-11	308.84	282	304	0.048	0.460	11.6	9.64E-04
53+00E	SP99-23-01	322.30	B12-filter	304.00	290	304	0.063	0.460	9.2	9.22E-04
53+00E	PN86-23-09	317.90	PN85-23-07	312.35	152	304	0.037	0.460	11.1	1.31E-03
53+00E	PN86-23-09	317.90	PN85-23-11	308.84	204	304	0.044	0.460	9.4	1.28E-03
53+00E	PN86-23-09	317.90	B12-filter	304.00	212	304	0.066	0.460	6.9	1.17E-03
53+00E	PN85-23-07	312.35	PN85-23-11	308.84	52	304	0.068	0.460	6.6	1.20E-03
53+00E	PN85-23-07	312.35	B12-filter	304.00	60	304	0.139	0.460	4.2	9.16E-04
75+00E	PN86-20-03	318.06	SP90-20-03	316.00	68	306	0.030	0.231	11.0	8.01E-04
75+00E	PN86-20-03	318.06	B13-filter	307.00	116	306	0.095	0.231	6.5	4.30E-04
75+00E	SP90-20-03	316.00	B13-filter	307.00	48	306	0.188	0.231	5.5	2.60E-04
80+00E	SP99-19-02	318.55	PN81-19-10	314.58	159	290	0.025	1.750	26.6	3.05E-03
80+00E	SP99-19-02	318.55	SP83-19-04	309.74	231	300	0.038	1.750	14.1	3.75E-03
80+00E	SP99-19-02	318.55	B14-filter	307.00	442	300	0.026	1.750	12.8	6.07E-03
80+00E	PN81-19-10	314.58	SP83-19-04	309.74	72	306	0.067	1.750	6.2	4.89E-03
80+00E	PN81-19-10	314.58	B14-filter	307.00	283	306	0.027	1.750	4.8	1.58E-02
80+00E	SP83-	309.74	B14-	307.00	211	306	0.013	1.750	2.4	6.58E-02

Cross-section	Up-stream tip	Up-stream head masl	Down-stream tip	Down-stream head masl	Distance between points m	Flow boundary base elevation masl	Gradient	Seepage flux m^3/m/day	Average flow area m^2/m	Permeability cm/s
	19-04		filter							
15+00 W	PN83-03-03	317.36	PN83-03-02	316.73	38	306	0.017	0.224	11.0	1.42E-03
15+00 W	PN83-03-03	317.36	SP94-03-01	317.18	42	306	0.004	0.224	11.3	5.37E-03
15+00 W	PN83-03-03	317.36	SP81-03-03	310.31	122	306	0.058	0.224	7.8	5.72E-04
15+00 W	PN83-03-02	316.73	SP94-03-01	317.18	4	306	-0.112	0.224	11.0	2.10E-04
15+00 W	PN83-03-02	316.73	SP81-03-03	310.31	84	306	0.076	0.224	7.5	4.51E-04
15+00 W	SP94-03-01	317.18	SP81-03-03	310.31	80	306	0.086	0.224	7.7	3.90E-04
15+00 W	SP81-03-04	309.05	SP81-03-01	310.39	21	306	-0.064	0.005	3.7	2.67E-05
26+00 W	PN91-04-05	336.82	PN86-04-05	331.61	206	310	0.025	0.410	24.2	7.74E-04
26+00 W	PN91-04-05	336.82	PN91-04-04	328.57	230	310	0.036	0.410	22.7	5.82E-04
26+00 W	PN91-04-05	336.82	B-02 filter	320.00	379	313	0.044	0.410	15.4	6.93E-04
26+00 W	PN86-04-05	331.61	PN91-04-04	328.57	24	312	0.127	0.410	18.1	2.07E-04
26+00 W	PN86-04-05	331.61	B-02 filter	320.00	173	313	0.067	0.410	12.8	5.52E-04
26+00 W	PN91-04-04	328.57	B-02 filter	320.00	149	313	0.058	0.410	11.3	7.30E-04
26+00 W	b-02 filter	320.00	SP90-04-22	321.66	287	317	-0.006	0.027	3.8	1.41E-03
26+00 W	SP90-04-22	321.66	SP90-04-08	320.20	133	318.5	0.011	0.022	2.4	9.51E-04
55+00 W	SP98-08-01	340.89	PN90-08-03	337.69	135	315	0.024	0.280	24.3	5.63E-04
55+00 W	SP98-08-01	340.89	SP90-08-04	332.78	168	316	0.048	0.280	20.8	3.22E-04
55+00 W	SP98-08-01	340.89	PN86-08-03	329.08	207	316	0.057	0.280	19.0	2.99E-04
55+00 W	SP98-08-01	340.89	B21-filter	322.00	244	316	0.077	0.280	15.4	2.71E-04
55+00 W	PN90-08-03	337.69	SP90-08-04	332.78	33	316	0.149	0.280	19.2	1.13E-04
55+00 W	PN90-08-03	337.69	PN86-08-03	329.08	72	316	0.120	0.280	17.4	1.56E-04
55+00 W	PN90-08-03	337.69	B21-filter	322.00	109	316	0.144	0.280	13.8	1.63E-04

Cross-section	Up-stream tip	Up-stream head masl	Down-stream tip	Down-stream head masl	Distance between points m	Flow boundary base elevation masl	Gradient	Seepage flux m^3/m/day	Average flow area m^2/m	Permeability cm/s
55+00 W	SP90-08-04	332.78	PN86-08-03	329.08	39	316	0.095	0.280	14.9	2.29E-04
55+00 W	SP90-08-04	332.78	B21-filter	322.00	76	316	0.142	0.280	11.4	2.01E-04
55+00 W	PN86-08-03	329.08	B21-filter	322.00	37	316	0.191	0.280	9.5	1.78E-04
55+00 W	B21-filter	322.00	SP83-08-05	323.72	60	317	-0.029	0.050	5.9	3.44E-04
61+00 W	PN85-09-02	334.08	PN85-09-03	328.97	53	317	0.096	0.300	14.5	2.48E-04
61+00 W	PN85-09-02	334.08	B-22 filter	322.00	93	317	0.130	0.300	11.0	2.42E-04
61+00 W	PN85-09-03	328.97	B-22 filter	322.00	40	317	0.174	0.300	8.5	2.35E-04
61+00 W	PN85-09-04	322.75	B-22 filter	322.00	-24	317	-0.031	0.050	5.4	3.45E-04
79+00 W	PN91-12-08	335.24	SP91-12-02	331.75	63	321	0.055	0.300	12.5	5.02E-04
79+00 W	PN91-12-08	335.24	B-17 filter	325.00	189	321	0.054	0.300	9.1	7.03E-04
79+00 W	SP91-12-02	331.75	B-17 filter	325.00	126	321	0.054	0.300	7.4	8.79E-04
20+00 W	PN91-03-05	329.17	SP93-03-02	321.00	131	305	0.062	0.413	20.1	3.82E-04
20+00 W	PN91-03-05	329.17	PN90-03-01	322.77	136	305	0.047	0.413	21.0	4.85E-04
20+00 W	PN91-03-05	329.17	B-02 filter	315.00	280	308	0.051	0.413	14.1	6.71E-04
20+00 W	SP93-03-02	322.42	PN90-03-01	322.77	5	308	-0.070	0.413	14.6	4.68E-04
20+00 W	SP93-03-02	322.42	B-02 filter	315.00	149	308	0.050	0.413	10.7	8.97E-04
20+00 W	PN90-03-01	322.77	B-02 filter	315.00	144	310	0.054	0.413	8.9	9.98E-04
72+00 W	SP98-11-02	342.63	PN91-11-14	323.78	77	320	0.245	0.250	13.2	8.95E-05
72+00 W	SP98-11-02	342.63	SP91-11-06	336.48	155	320	0.040	0.250	19.6	3.73E-04
72+00 W	SP98-11-02	342.63	SP94-11-01	332.48	185	321	0.055	0.250	16.6	3.19E-04
72+00 W	SP98-11-02	342.63	B21-filter	327.00	230	322	0.068	0.250	12.8	3.32E-04
72+00 W	PN91-11-14	323.78	SP91-11-06	336.48	78	320	-0.163	0.250	10.1	1.75E-04
72+00	PN91-	323.78	SP94-	332.48	108	320	-0.081	0.250	8.1	4.42E-04

Cross-section	Up-stream tip	Up-stream head masl	Down-stream tip	Down-stream head masl	Distance between points m	Flow boundary base elevation masl	Gradient	Seepage flux m^3/m/day	Average flow area m^2/m	Permeability cm/s
W	11-14		11-01							
72+00 W	PN91-11-14	323.78	B21-filter	327.00	153	320	-0.021	0.250	5.4	2.55E-03
72+00 W	SP91-11-06	336.48	SP94-11-01	332.48	30	320	0.133	0.250	14.5	1.50E-04
72+00 W	SP91-11-06	336.48	B21-filter	327.00	75	321	0.126	0.250	10.7	2.13E-04
72+00 W	SP94-11-01	332.48	B21-filter	327.00	45	321	0.122	0.250	8.7	2.72E-04
72+00 W	B21-filter	327.00	SP98-11-04	335.53	157	324	-0.054	0.050	7.3	1.47E-04
72+00 W	B21-filter	327.00	SP98-11-05	334.53	361	325	-0.021	0.050	5.8	4.81E-04
72+00 W	SP98-11-04	335.53	SP98-11-05	334.53	204	326	0.005	0.050	9.0	1.31E-03
67+00 W	PN85-10-02	333.26	PN85-10-04	329.42	68	320	0.056	0.260	11.3	4.70E-04
67+00 W	PN85-10-02	333.26	B-21 filter	325.00	75	320	0.110	0.260	9.1	2.99E-04
67+00 W	PN85-10-04	329.42	B-21 filter	325.00	7	320	0.631	0.040	7.2	1.02E-05
100+50 W	SP96-16-01	328.90	SP96-16-06	324.29	52	320	0.089	0.280	6.6	5.54E-04
100+50 W	SP96-16-01	328.90	B17 filter	323.00	69	320	0.086	0.280	5.9	6.37E-04
100+50 W	SP96-16-06	324.29	B17 filter	323.00	17	320	0.076	0.280	3.6	1.17E-03
102+00 E	SP98-16-10	335.96	SP91-16-09	327.95	173	320	0.046	0.280	12.0	5.85E-04
102+00 E	SP98-16-10	335.96	SP96-16-07	325.04	214	320	0.051	0.280	10.5	6.05E-04
102+00 E	SP98-16-10	335.96	B17-filter	323.00	241	320	0.054	0.280	9.5	6.36E-04
102+00 E	SP91-16-09	327.95	SP96-16-07	325.04	41	321	0.071	0.280	5.5	8.31E-04
102+00 E	SP91-16-09	327.95	B17-filter	323.00	68	321	0.073	0.280	4.5	9.95E-04
102+00 E	SP96-16-07	325.04	B17-filter	323.00	27	321	0.076	0.280	3.0	1.42E-03
95+00E	SP98-17-02	337.38	PN91-17-07	338.22	15	316	-0.056	0.287	21.8	2.72E-04
95+00E	SP98-17-02	337.38	B-16 filter	319.00	196	316	0.094	0.287	12.2	2.91E-04
95+00E	PN91-17-07	338.22	B-16 filter	319.00	181	316	0.106	0.287	12.6	2.48E-04

Cross-section	Up-stream tip	Up-stream head masl	Down-stream tip	Down-stream head masl	Distance between points m	Flow boundary base elevation masl	Gradient	Seepage flux m^3/m/day	Average flow area m^2/m	Permeability cm/s
85+00E	PN88-18-16	321.74	PN84-18-05	310.68	164	297	0.067	0.876	19.2	7.82E-04
85+00E	PN88-18-16	321.74	B-14 filter	305.00	218	297	0.077	0.876	16.4	8.06E-04
85+00E	PN84-18-05	310.68	B-14 filter	305.00	54	303	0.105	0.876	4.8	1.99E-03
88+00E	SP98-18-02	332.28	PN86-18-01	332.84	31	307	-0.018	0.876	25.6	2.19E-03
88+00E	SP98-18-02	332.28	PN85-18-04	330.11	93	307	0.023	0.876	24.2	1.80E-03
88+00E	SP98-18-02	332.28	PN85-18-15	329.70	140	307	0.018	0.876	24.0	2.29E-03
88+00E	SP98-18-02	332.28	B14-filter	315.00	315	307	0.055	0.876	16.6	1.11E-03
88+00E	PN86-18-01	332.84	PN85-18-04	330.11	62	307	0.044	0.876	24.5	9.40E-04
88+00E	PN86-18-01	332.84	PN85-18-15	329.70	109	307	0.029	0.876	24.3	1.45E-03
88+00E	PN86-18-01	332.84	B14-filter	315.00	284	307	0.063	0.876	16.9	9.53E-04
88+00E	PN85-18-04	330.11	PN85-18-15	329.70	47	307	0.009	0.876	22.9	5.07E-03
88+00E	PN85-18-04	330.11	B14-filter	315.00	222	307	0.068	0.876	15.6	9.57E-04
88+00E	PN85-18-15	329.70	B14-filter	315.00	175	307	0.084	0.876	15.4	7.86E-04
72+00E	SP99-20-04	316.23	PN88-20-03	317.28	56	300	-0.019	0.231	16.8	8.52E-04
72+00E	SP99-20-04	316.23	PN90-20-06	313.96	132	305	0.017	0.231	10.1	1.54E-03
72+00E	SP99-20-04	316.23	B-13 filter	307.00	143	306	0.065	0.231	5.6	7.39E-04
72+00E	PN88-20-03	317.28	PN90-20-06	313.96	76	307	0.044	0.231	8.6	7.11E-04
72+00E	PN88-20-03	317.28	B-13 filter	307.00	87	307	0.118	0.231	5.1	4.41E-04
72+00E	PN90-20-06	313.96	B-13 filter	307.00	11	307	0.633	0.231	3.5	1.22E-04
64+00E	SP99-21-02	321.91	SP90-21-03	314.19	74	297	0.104	0.231	21.1	1.22E-04
64+00E	SP99-21-02	321.91	SP90-21-02	307.48	127	297	0.114	0.231	17.7	1.33E-04
64+00E	SP99-21-02	321.91	B-12 filter	306.00	160	297	0.099	0.231	17.0	1.59E-04
64+00E	SP90-	314.19	SP90-	307.48	53	297	0.127	0.231	13.8	1.53E-04

Cross-section	Up-stream tip	Up-stream head masl	Down-stream tip	Down-stream head masl	Distance between points m	Flow boundary base elevation masl	Gradient	Seepage flux m³/m/day	Average flow area m²/m	Permeability cm/s
	21-03		21-02							
64+00E	SP90-21-03	314.19	B-12 filter	306.00	86	297	0.095	0.231	13.1	2.15E-04
64+00E	SP90-21-02	307.48	B-12 filter	306.00	33	297	0.045	0.231	9.7	6.13E-04
44+00E	PN87-24-08	323.32	PN87-24-09	321.05	76	308	0.030	0.455	14.2	1.24E-03
44+00E	PN87-24-08	323.32	PN85-24-01	320.23	81	308	0.038	0.455	13.8	1.00E-03
44+00E	PN87-24-08	323.32	B-12 filter	311.00	185	308	0.067	0.455	9.2	8.64E-04
44+00E	PN87-24-09	321.05	PN85-24-01	320.23	5	308	0.164	0.455	12.6	2.54E-04
44+00E	PN87-24-09	321.05	B-12 filter	311.00	109	308	0.092	0.455	8.0	7.12E-04
44+00E	PN85-24-01	320.23	B-12 filter	311.00	104	308	0.089	0.455	7.6	7.80E-04
47+00E	PN86-24-02	325.19	PN86-24-01	322.12	61	305	0.050	0.455	18.7	5.61E-04
47+00E	PN86-24-02	325.19	PN85-24-09	317.95	115	305	0.063	0.455	16.6	5.05E-04
47+00E	PN86-24-02	325.19	PN84-24-03	311.34	174	305	0.080	0.455	13.3	4.99E-04
47+00E	PN86-24-02	325.19	B-12 filter	309.00	211	305	0.077	0.455	12.1	5.68E-04
47+00E	PN86-24-01	322.12	PN85-24-09	317.95	54	305	0.077	0.455	15.0	4.54E-04
47+00E	PN86-24-01	322.12	PN84-24-03	311.34	113	307	0.095	0.455	9.7	5.68E-04
47+00E	PN86-24-01	322.12	B-12 filter	309.00	150	307	0.087	0.455	8.6	7.04E-04
47+00E	PN85-24-09	317.95	PN84-24-03	311.34	59	307	0.112	0.455	7.6	6.15E-04
47+00E	PN85-24-09	317.95	B-12 filter	309.00	96	307	0.093	0.455	6.5	8.73E-04
47+00E	PN84-24-03	311.34	B-12 filter	309.00	37	307	0.063	0.455	3.2	2.63E-03
11+00E	PN92-28-01	312.59	PN83-29-01	308.39	115	305	0.037	0.484	5.5	2.79E-03

Note: Negative gradients indicate flow in the upstream direction
Database numbers G-227 through G-456

Each analysis was subjectively assigned a good, fair, or poor rating depending upon the reliability of the analysis – how well the conditions and the geometry fit the model. Perhaps surprisingly, the values and distribution of each between the 20th and 80th percentiles for each class were almost identical. The poor series did have a few more low permeability values, the fair series has a few high permeability values compared to the other distributions. Some of the calculated permeabilities are rather high due to the influence of the gravel foundation conditions under the east side of MLSB which is not accounted for in this simplified method of analyses.

The method is quick and useful, but is less precise than the finite element seepage back analysis which handles the boundary conditions much better than the above method.

5.11 Office dyke section gradients analyses

This method is similar to that listed above for gradient analysis, but simply uses the pond and the main downstream filter as two end points where the heads are known. It is assumed that the beach below the pond is saturated or nearly so (probably mostly true for most sections). It ignores percolation of rainfall, evapotranspiration. And it assumes that the cross-section is uniform in lateral extent (ignoring the inside and outside corners of the pond). Results are listed in Table D-17 below.

Table D-17 Results from pond to toe gradient analyses

Database number	Location	Section Number	Permeability cm/s
G-426	MLSB Cell 2	E08+60	2.31E-04
G-427	MLSB Cell 3	E102+00	3.20E-04
G-428	MLSB Cell 8	E11+00	4.40E-04
G-429	MLSB Cell 6/7	E18+00	5.39E-04
G-430	MLSB Cell 4	E24+00	6.22E-04
G-431	MLSB Cell 4	E32+00	7.24E-04
G-432	MLSB Cell 17	E40+00	9.51E-04
G-433	MLSB Cell 9	E44+00	9.78E-04
G-434	MLSB Cell 18	E47+00	9.93E-04
G-435	MLSB Cell 5	E53+00	1.19E-03
G-436	MLSB Cell 6	E64+00	1.29E-03
G-437	MLSB Cell 10	E72+00	1.75E-03
G-438	MLSB Cell 12	E75+00	1.78E-03
G-439	MLSB Cell 16	E80+00	1.90E-03
G-440	MLSB Cell 18	E85+00	2.14E-03
G-441	MLSB Cell 11	E88+00	2.25E-03
G-442	MLSB Cell 16	E95+00	4.60E-03
G-443	MLSB Cell 23	W04+00	1.99E-04
G-444	MLSB Cell 24	W10+00	2.15E-04
G-445	MLSB Cell 24	W100+50	2.43E-04
G-446	MLSB Cell 1	W15+00	4.26E-04
G-447	MLSB Cell 21	W20+00	9.90E-05
G-448	MLSB Cell 20	W26+00	9.98E-05
G-449	MLSB Cell 20	W31+00	1.15E-04
G-450	MLSB Cell 25	W37+00	2.29E-04
G-451	MLSB Cell 27	W43+00	3.43E-04
G-452	MLSB Cell 26	W55+00	4.90E-04
G-453	MLSB Cell 28	W61+00	5.39E-04
G-454	MLSB Cell 29	W67+00	6.24E-04
G-455	MLSB Cell 29	W72+00	7.00E-04
G-456	MLSB Cell 19	W79+00	1.52E-03

There is some duplication with the full cross-section back-analysis through seepage analysis – in general, this analysis by sections provides an answer about 1.5x that of the full seepage analysis (a range of 0.5 to 4.0). In general, the closeness of the results add credence and support to this simple method – a method usually reserved for back-of-the-envelope calculation. Both distributions are similar. The result is that within a few minutes, one can estimate the permeability of a homogeneous reasonably accurately from first principles using nothing more than pen and paper – a useful skill.

5.12 Office dyke design values

While not a true measure of permeability, the database includes values assumed in analysis by professional engineers and geologists from staff and consultants reports. Most are used for seepage design for dyke cross-sections. Typically, consultants will analyze the most recent geometry and flows from the structure, determine a horizontal permeability (from the back analysis) and assume a vertical permeability as a fraction of the horizontal value.

In most cases, for geotechnical dam design, it is conservative to assume a slightly high value of permeability (to ensure seepage design methods are not underdesigned for seepage discharge flows[3]). A new perspective is that a conservatively high value of tailings permeability may be unconservative for other, sometimes competing, landscape performance goals such as controlling fluxes to within certain ranges, and for water table location.

The choice of permeability for design is partly a matter of style and personality. Different values have been used by different consultants (AMEC Earth and Environmental and its predecessor companies, Klohn Crippen (and its predecessors), Norwest Mine Services, Suncor, Syncrude, and Thurber Engineering). Prior to 1987, a k_h=2x10-4 cm/s was the most common design value and after 1990, $k_h=8\times10^{-4}$ cm/s was preferred. Prior to 1987, k_h/k_v ratios from 1 through 16 were employed, whereas after 1990, a value of 16 predominates.

The design, predicted, and actual performance are more important than the choice of design value and one cannot say that any particular design value within the ranges employed was better or worse than another. That later, as discussed later, this report provides a better survey of average values and their ranges than previously available. The results presented later suggest that the average back-analyzed values (which also contain a certain amount of style) is 5×10^{-4} cm/s with a typical range from 1×10^{-4} to 1×10^{-3} cm/s with k_h/k_v ratio of 10 being pretty good for this kind of analysis.

Probably more important is the recognition that the permeability is a function of scale and to a lesser extent of test method, and that calibration using the model that will also be used for design is required rather than extending these geotechnical design values to surface water infiltration or pumping uses.

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[3] Even given a conservative permeability, it is common and prudent practice to employ a factor of safety of five on the discharge flows for design of dyke seepage filters and drains.

Of historical note, rainfall percolation was never considered before about 1990 – it was overlooked in all consultants reports. Starting in about 1990, most of the reports indicated that precipitation and evaporation were assumed about equal (no net percolation), and the analysis continued as before. It is only in 1996 that percolation was used in analysis, but is probably still not a standard consideration in dyke design. As the beaches, downstream slopes, and toe berms become longer, this percolation comes to dominate the water inputs, often swamping that of the pond, sometimes reversing the flow at the pond, making the pond a net recharge (upward flow) area. Incorporation of percolation water is still not state of practice for most dyke seepage work, and it is only recently that commercially available software can easily handle this boundary condition. Determination of percolation rates remains more of an art than a science.

Data is summarized in Table D-18 below.

Table D-18 Results from review of design values

Data-base number	Horizontal permeability cm/s	Vertical permeability cm/s	k_h/k_v ratio	Note	Program
G-001	1.60E-04	1.00E-05	16	Compacted	MLSB Design Hardy 1977
G-002	1.00E-03	1.00E-03	1	Uncompacted	
G-003	1.60E-04	1.00E-05	16	Compacted	MLSB Filters Syncrude 1983
G-004	1.00E-03	1.00E-03	1	Uncompacted	
G-006	2.00E-03	1.25E-04	16		SWSS Design Klohn 1991
G-063	8.00E-04	5.00E-05	16	Upper bound	SWSS Landscape Design 1996 Syncrude/AGRA 1997
G-064	1.00E-04	6.25E-06	16	Lower bound	
G-068	1.60E-04	1.00E-05	16	Based on piezo tests	Seepage Analysis Syncrude 1980
G-084	8.00E-04	5.00E-05	16	Generally accepted dyke design number	Seepage SWSS 1996 Syncrude 1996
G-086	1.56E-03			Based on grainsize	MFT Spiking 1994 Syncrude 1995
G-150	1.60E-03	1.00E-04	16		Toe Berm Application Klohn 1990
G-152	7.00E-03	4.38E-04	16		Toe berm design HBT AGRA 1992
G-154	4.00E-03	1.00E-03	4	Cell	Syncrude in-pit berm Hardy HBT Ltd 1986
G-155	4.00E-03	4.00E-03	1	Beach	
G-156	2.00E-03	1.25E-04	16	Cell toe (graded)	
G-159	8.00E-04	5.00E-05	16		MLSB Design Syncrude 1999
G-176	8.00E-04	5.00E-05	16		Syncrude seepage analysis Syncrude 1994
G-177	8.00E-04	8.89E-05	9	Upper bound	SWSS Seepage Study AGRA 1996
G-178	8.00E-04	5.00E-05	16	Lower bound	
G-179	1.00E-04	1.11E-05	9	Upper bound	
G-180	1.00E-04	6.25E-06	16		
G-182	1.00E-03			To depths of 60ft, uncompacted, lower bound	Suncor TID 1977 Suncor 1977
G-183	1.00E-03			From 60-100ft, uncompacted, upper bound	
G-184	1.00E-04			From 60-100ft, uncompacted, lower bound	
G-185	5.00E-05			Below 100ft, uncompacted, upper bound	
G-186	3.00E-05			Below 100ft, uncompacted, lower bound	
G-187	1.00E-03			Compacted 5-10ft, lower bound	

Data-base number	Horizontal permeability cm/s	Vertical permeability cm/s	k_h/k_v ratio	Note	Program
G-188	1.00E-04			Compacted, upper bound	
G-189	1.00E-05			Compacted, lower bound	
G-191	2.00E-02	5.00E-03	4	From piles of test tailings and used for initial Suncor design	
G-192	5.00E-04	5.56E-05	9	Review board recommendations p127, compacted	
G-193	2.00E-03	6.67E-04	3	Review board recommendations p127, uncompacted at a depth of about 30-40ft	
G-208	2.00E-05		16		SWSS Buried Channel Aquifer Klohn 1990
G-209	2.00E-04	1.25E-05	16	Hydraulically placed	Cell 11+12 toe berm Thurber 1990
G-210	2.00E-03	1.25E-04	16		
G-211	2.00E-04	5.00E-05	4		
G-212	2.00E-03	5.00E-04	4		
G-213	2.00E-04	5.00E-05	4	Mobile equipment placed	
G-214	2.00E-03	5.00E-04	4		
G-215	2.00E-04	2.00E-04	1		
G-216	2.00E-03	2.00E-03	1		
G-217	1.60E-04	1.00E-05	16		Seepage control risk assessment Thurber 1986
G-218	1.00E-03			Sensitivity	
G-219	1.60E-04	1.00E-05	16		Seepage Section 53660 mN Syncrude 1980
G-222	2.00E-03	1.20E-04	16	Based on analysis of MLSB	OSLO Design Klohn 1991
G-226	2.00E-03	1.20E-04	16		Mildred Lake East Toe Berm design Klohn 1997

5.13 Office dyke section back analysis

Thirty three instrumented cross-sections from MLSB and four from the SWSS were back-analyzed using Seep/W. The year-end 1998 condition was used for MLSB and the October 1999 condition was used for SWSS. Details of the method are provided in Supplement 1 and summarized here and in Chapter 6 of this thesis.

The geometries extended from upstream some 300 m into the pond to the downstream toe of the structure and included an impermeable base (either directly below the tailings sand where it lies immediately on top of glacial till or glaciolacustrine clay or below a glaciofluvial aquifer.) It was assumed that 20 percent of annual precipitation percolated into the structure and that the structure was essentially at steady state seepage. For the SWSS, 40 percent of precipitation was assumed for the active beaches based on data from a lysimeter test.

The sections were back analyzed to match piezometric data and total flux, with an emphasis on matching the flux as closely as possible. In most cases, matching the piezometric conditions was relatively easy. In ones that were hard, a 'fair' quality designation was assigned. Where matches were poor or geometries poorly defined, a 'poor' quality designation was assigned.

Steady-state finite element analysis was performed using Seep/W (version 4.21) was used (Geoslope International Ltd 1998.) As described for the gradient analysis above, the test scale length was 700 to 1600 m with a corresponding test volume of 3 million to 15 million m^3. Results are presented in Table D-19 below.

Table D-19 Results from dyke section seepage finite element back analysis

Section	Permeability (horizontal) cm/s	Permeability (vertical) cm/s	Permeability ratio (k_h/k_v)
W04+00	4.00E-04	2.50E-05	16
W10+00	3.20E-04	2.00E-05	16
W15+00	2.00E-04	1.25E-05	16
W20+00	4.00E-04	4.00E-06	100
W26+00	5.00E-04	3.13E-05	16
W31+00	8.00E-04	5.00E-05	16
W37+00	7.00E-04	4.38E-05	16
W43+00	4.00E-04	2.50E-05	16
W55+00	2.20E-04	1.38E-05	16
W61+00	4.00E-04	2.50E-05	16
W67+00	5.00E-04	3.13E-05	16
W72+00	4.00E-04	4.00E-04	1
W79+00	8.00E-04	5.00E-05	16
W102+00	7.00E-04	4.38E-05	16
E100+50	3.50E-03	3.50E-05	100
E95+00	2.49E-04	2.49E-05	10
E88+00	1.00E-03	6.25E-05	16
E85+00	7.00E-04	7.00E-04	1
E80+00	1.60E-03	1.00E-04	16
E75+00	2.20E-04	1.38E-05	16
E72+00	2.40E-04	1.50E-05	16
E64+00	2.50E-04	1.56E-05	16
E53+00	1.00E-04	6.25E-06	16
E47+00	4.20E-04	2.63E-05	16
E44+00	1.50E-04	9.38E-06	16
E40+00	1.50E-04	1.50E-06	100
E32+00	1.00E-04	6.25E-06	16
E24+00	2.00E-04	1.25E-05	16
E18+00	7.00E-04	4.38E-05	16
E11+00	4.00E-04	2.50E-05	16
E09+00	6.00E-04	3.75E-05	16
E08+60	3.00E-04	1.88E-05	16
E08+00	7.00E-04	4.38E-05	16
Cell 31	8.00E-04	5.00E-05	16
Cell 48	8.00E-04	5.00E-05	16
Cell 49	1.00E-03	6.25E-05	16
Cell 51	6.00E-04	3.75E-05	16

Note: A k_h/k_v ratio of 16 was used for the initial runs and only adjusted if a good fit to the phreatic surface was not achieved.

5.14 Office dyke section back analysis (historical)

This section is very similar to the one immediately above, but provides final back-analyzed values from consultants reports from 1977, 1979, 1990, and 1992. Some of the analyses were done graphically by hand with flow nets, others were done with early finite element models and were based on piezometric heads and measured seepage discharges. All recharge was assumed to come from the tailings pond. Blinding by MFT in the tailings pond was not considered. All discharge was assumed to report to internal filter drains.

Analysis were run on dykes that were still under construction and hence were smaller than those analyzed in for this study. In most cases, the sections were several hundred metres long. Table D-12 provides the results of this review.

Table D-20 Results from dyke section back analyses 1977-1992

Data-base number	Horizontal permeability cm/s	Vertical permeability cm/s	kh/kv ratio	Note	Program
G-005	2.00E-04	1.25E-05	16		MLSB Design Thurber 1990
G-065	1.00E-03	1.00E-04	10		MLSB Paper Syncrude 1986
G-066	1.00E-04	1.00E-05	10	Compacted	Seepage paper Klohn 1979
G-067	1.00E-03	1.00E-03	1	Uncompacted	
G-151	2.00E-03	1.25E-04	16		Toe berm design Klohn 1990
G-153	2.00E-03	1.25E-04	16	Considered k_h/k_v ratios of 1 to 25	Syncrude in-pit berm HBT AGRA 1992
G-158	2.00E-03	1.25E-04	16	Cell 4	Syncrude toe berm Thurber 1990
G-197		7.00E-05		Flow measurements	Suncor TID 1977
G-198		1.20E-05		Time lag	Suncor 1977

The actual modelling methods or the actual analyzed values are probably not as important as using consistent assumptions and modelling between back-analysis and design, and ensuring that the extrapolation to future geometries or changes in filter designs does not stray too far from the back-analysis. Thus the back-analysis / design method is a semi-empirical calibration method. It also clearly points out that the back-analyzed value, often thought to be the best possible, is considerably influenced by style.

5.15 Summary

The data are summarized in Table D-4 and discussed in Chapter 6 of this thesis. Appendix C provides a listing of the database of permeability values arranged by test number.

6.0 References

This section contains references for the above text along with papers and books that relate to seepage and groundwater that may be useful for landscape engineering. Some references are incomplete; some others are internal to Syncrude. Other references are available in Chapter 6.

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Supplement A

Seepage analysis methods for office dyke cross-section back analysis

Seepage analysis of tailings dyke cross-sections was carried out to back-analyzed bulk tailings sand permeability. Additionally, it was provided insight about the relative contributions of various inflows and outflows and a better understanding of seepage regimes of these large structures. Finally, the large number of regulatory spaced sections permits development of a geostatistical database for spatial distribution of tailings sand permeability at large scales.

The following steps were used to do the analysis.

1. Cross sections

Geological / instrumentation cross-sections developed by Syncrude staff formed the basis of the analyses. These sections are at 1:1000 and 1:2000 scale (horizontal) with 5x vertical exaggeration. Hydrology information at December 1998 was penned onto the cross-sections – hydraulic heads from piezometers, filter drainage flow rates, pond locations, etc.

2. Geometry

For the y-axis, actual elevations were used. These ranged from 290 to –353 masl for Mildred Lake Settling Basin (MLSB). For the x-axis, the dyke centreline (usually the downstream crest) was arbitrarily set at x=2000 m.

It was found at MLSB that the geometry could be simplified to ignore berms and ramps. Toe berms were included in the geometry. Pond elevation sin 190998 was y = 347 masl. The upstream area was extended 300 m into the pond with a beach slope of nominally one percent (actual beach slopes may differ). Thus the analysis started at y = 344 m with an initial head of 347 m. Where a high permeability layer extended form the toe to beyond the pond, a 500-m blinded zone (from the MFT) was employed in the model – for other analyses, this was not required.

3. Geology

The geological interpretation on the cross-sections was assumed to be adequate (and seemed reasonable). The geologic investigations shown in these cross-sections were primarily aimed at slope stability and focussed on bedrock geology. Little work has been focussed on surficial aquifers under the dyke, other than noting their tops and bottom elevations and material types. Generally, the information available provides reasonable confidence in seepage analyses.

Most basal geology units were presumed to be aquitards for the present analysis. The glaciolacustrine sediments (Pl) and the glacial tills (Pg), the McMurray Formation oil sand (Km) and the Clearwater Formation (Kc) were assigned no-flow boundaries. Glaciofluvial sands and gravels (Pf) and one area of thick muskeg (Ho) were found to be more permeable than the tailings sand and were analyzed as confined aquifers acting like blanket toe drains.

The tailings sand was assumed to be homogeneous within each section – no subdivision was made for cell compacted, resloped, or beach sands. Filter drains were assumed to be free-draining. Surficial conditions were not differentiated between reclaimed and unreclaimed – a uniform percolation rate bound conditions was employed.

4. Material properties

As a starting basis for each analysis, tailings sand was assumed to have a permeability of 8 x 10^{-4} cm/s with a $k_v/k_h=1/16 = 0.0625$. A soil water characteristic curve based on a typical result (GT 35610) from recent laboratory testing (Gan and McKenna 2001) was used – though this value is less important for steady-state analyses because the capillary fringe is so small (usually < 30cm thick).

Pf sand and Ho muskeg were started with $k_h = k_v = 1 \times 10^{-3}$ cm/s. All other materials were assumed to be impermeable for the analysis.

5. Boundary conditions

The vertical boundary under the pond was assumed to be impermeable (q = 0, no review) as was the lower (basal) boundary. The pond was assumed to be at a constant head (H = 347 m). The tailings sand beach, crest, and downstream slopes and berms were assigned a recharge boundary flux equal to 20% of annual precipitation (20% of 450 mm = 90 mm/yr = 2.85 x 10^{-9} cm/s). A flux boundary (q) with review by elevation was employed. The filter drain was created by deletion of interior elements to form the design shape and a flux boundary (q = 0) with review by maximum pressure employed. Sometimes, the converged solutions were non-sensible, and in these cases, good results were achieved by changing the flux boundary of internal drains to review by elevation.

6. Analysis method

Steady state analysis methods were employed. Water balances were based on yearly average conditions. Detailed steps are listed below.

a. Create a base file with typical scale, axes, material types, and permeability and volumetric water content functions

b. Adjust scale, axis, and grid to match geologic cross-section. Use 5H:1V exaggeration.

c. Using drawing tool, trace out geology and geometry of simplified section.

d. Use 'draw multiple elements' tool to fill cross-section with elements. Most cross-sections use a grid of about 30 elements in the x-direction (20 to 60 m spacing) and 20 m in y-direction (2 m spacing) for a total of 400 to 800 elements.

e. Adjust nodes to fit geology and geometry. Assign material types. Make element thickness equal to 86400 so that seepage fluxes are converted from $m^3/m/s$ to $m^3/m/day$ (there are 24 x 60 x 60 = 86400 seconds in a day).

f. Assign boundary conditions. Sort elements.

g. Add seepage flux sections to pond, beach, slope, drains, and drain bypass areas.

h. Run analysis. Plot contours of total heads in 2-m increments.

i. Adjust k_h function for tailings sand to match measured drainage fluxes and location of phreatic surface (or to match hydraulic heads recorded by standpipes). (Sometimes it helps to relocate a node where to where a hydraulic head measurement is available.

j. Record inflows, outflows, and back-analyzed parameters. Plot grid and total head sections.

k. On selected cross-sections, consider effect of grid size, permeability ratio, permeability changes, percolation rate, and beach and pond geometry.

Each section requires about 60 to 90 minutes to analyze (after sorting out the details on the first few sections which took much longer). Most of the time is spent inputting the geometry and elements. In general, the analysis converged well to reasonable solutions, with each run taking about 20 seconds. About 20 different analyses were run for each section to arrive at a reasonably good fit for the parameters.

Additional information about the analysis of each section is provided in Table D-21. Results of the work are provided in D-19 and in Chapter 6 of this thesis.

Table D-21 Dyke seepage cross-section finite element back-analysis – general notes and comments

Section	Location	Geometry / geology notes	Analysis notes
E08+00	MLSB Cell 29	• Very long beach (900 m) • Three filters, only B filter is operating. • Through-going 2m Pf aquifer. • Short steep downstream face • Very close to 2 adjacent sections.	• Easy to analyze • No piezometer control on this section, just need to keep below filters. • Could change both permeability of TS and Pf to get the same answer. • $k_h = 7 \times 10^{-4}$ cm/s • $k_{PF} = 1 \times 10^{-3}$ cm/s • Might want to look at adjacent standpipe sections. • GOOD
E08+60	MLSB Cell 29	• Very long beach (1000 m) • Three filters, only B filter is operating. • Through-going 2m Pf aquifer, with Ho aquifer at the toe. • Short steep downstream face	• Easy to analyze • Fits piezometers fairly well. • $k_h = 3 \times 10^{-4}$ cm/s • $k_{PF} = 3 \times 10^{-3}$ cm/s • GOOD
E09+00	MLSB Cell 29	• Very long beach (1000 m) • Three filters, only B filter is operating. • Through-going 2m Pf aquifer overlain by thin Ho aquifer. • Short steep downstream face • Very close to 2 adjacent sections.	• Easy to analyze • Good match with piezometers • $k_h = 6 \times 10^{-4}$ cm/s • $k_{PF} = 2 \times 10^{-3}$ cm/s • GOOD
E11+00	MLSB Cell 29	• Long beach (1000 m) • Very thick Pf sand aquifer underneath • Only B-filter active • Steep downstream face	• Easy to analyze • Good match with piezometers • $k_h = 4 \times 10^{-4}$ cm/s • $k_{PF} = 4 \times 10^{-3}$ cm/s • GOOD
E18+00	MLSB Cell 28	• Long beach (1050 m) • Steep downstream face • Only B-filter active • Low water table • Moderately thick Pf aquifer under beach and downstream face.	• Easy to analyze • Good match with piezometers • $k_h = 7 \times 10^{-4}$ cm/s • $k_{PF} = 5 \times 10^{-3}$ cm/s • GOOD
E24+00	MLSB Cell 27	• Long beach (1000 m) • Only B-filter is active, but at very little flow (most goes out aquifer). • Thick Pf aquifer throughout. • Very steep downstream face	• A bit tricky to analyze • Had to extend blinded zone under pond to allow for upstream flow. • Good match with piezometers, but few piezometers. • Interesting flow patterns at pond due to through-going aquifer. • Needed to invoke very high permeability in Pf aquifer.

Section	Location	Geometry / geology notes	Analysis notes
			• $k_h = 2 \times 10^{-4}$ cm/s • $k_{PF} = 10 \times 10^{-3}$ cm/s • FAIR
E32+00	MLSB Cell 26	• Long beach (750 m) • Only B-filter is active, but at very little flow (most goes out aquifer). • Variable thickness Pf aquifer throughout. • Steep downstream face	• A bit tricky to analyze • Had to extend blinded zone under pond to allow for upstream flow. • Water table analyzed a bit lower than piezometer at crest. • Interesting flow patterns at pond due to through-going aquifer. • Needed to invoke very high permeability in Pf aquifer. • $k_h = 1 \times 10^{-4}$ cm/s • $k_{PF} = 10 \times 10^{-3}$ cm/s • FAIR
E40+00	MLSB Cell 25	• Medium beach (300 m) • Long continuous Pf sand aquifer underneath • Steep slope • Three filters, only B filter is active	• Hard to analyze, especially with drain sitting right on top of Pf aquifer. • Best fit happened when switched kv/kh to 1/100 (minor change in Kh) • Interesting flow patterns around active filter, very sensitive to k values. • $k_v/k_h = 0.01$ • $k_h = 1.5 \times 10^{-4}$ cm/s • $k_{PF} = 1 \times 10^{-3}$ cm/s • FAIR
E44+00	MLSB Cell 24	• Short beach 100 m • Partially penetrating thin basal Pf aquifer (had to extend farther upstream to make piezo surface work out) • Toe berm partially constructed 1998 (keeps basal aquifer pressures higher)	• Difficult to analyze, main problem was getting pore-pressures under crest low enough – had to extend basal aquifer – perhaps there are 3D effects in plan view • $k_h = 1.5 \times 10^{-4}$ cm/s • $k_{PF} = 1 \times 10^{-3}$ cm/s • POOR
E47+00	MLSB Cell 24	• Short beach 100 m • Partially penetrating thin basal Pf aquifer • Moderate flow through B-filter.	• Fairly easy to analyze, • $k_h = 4.2 \times 10^{-4}$ cm/s • $k_{PF} = 2 \times 10^{-3}$ cm/s • Fair match with piezometers. • FAIR
E53+00	MLSB Cell 23	• Assume no toe berm (1998 profile) • A little tricky with the Ho and Pf. Not all that well defined. • Ho and Pf underlay, but perhaps not continuous. Muskeg likely sealed off under high load •	• Took all day to analyze – had to fix problems with Ho under crest and filter boundary conditions • In the end, the analysis came to a single combination that seems to fit pretty well. • Most of the inflow occurs at the end of the beach closest to crest.

Section	Location	Geometry / geology notes	Analysis notes
			• $k_h = 1x10^{-4}$ cm/s • $k_{PF} = 2x10^{-3}$ cm/s • FAIR
E64+00	MLSB Cell 21	• Very short beach and steep slope • Underlain by starter dyke and through going 5m thick Pf4 sand. • Three filters (D, C, B).	• $k_h = 2.5 \times 10^{-4}$ cm/s • $k_{PF} = 5 \times 10^{-3}$ cm/s • Could probably adjust kh/kv lower to get more flow to lower filter and reduce Kpf. • Analyses fairly well, but had to delete upper filter. Reasonably good analysis, geology fairly good. • GOOD
E72+00	MLSB Cell 20	• Short slope underlain by 5m thick Pf well under pond • Starter toe dyke built on Pf • D, C, B, and A filter, of which only B is really flowing. • Short beach. • Long blinded zone modelled • Concave corner at edge of new toe berm.	• More variables than equations. Likely can get several fits. • $k_h = 2.4x10^{-4}$ cm/s • $k_{PF} = 5.5x10^{-3}$ cm/s • This seems the best fit for piezometers too. Likely other combinations of permeability would work with slightly different water tables. • Fluxes through gravel seem very high. • Interesting unsaturated zone under blinded MFT predicted. • FAIR
E75+00	MLSB Cell 20	• Short beach (215m) • Small aquifer under starter dyke • Steep slope • Pf3 layer of unknown properties	• Largest uncertainty is aquifer properties (thickness and permeability) under starter dyke. • $k_h = 2.2 \times 10^{-4}$ cm/s • $k_{PF} = 1 \times 10^{-3}$ cm/s • Fairly good fit to piezometric surface. • FAIR
E80+00	MLSB Cell 19	• Complex geometry of a short beach (340 m), underlain by long sand, starter dyke on sand, three filters operating. • D filter showing more flow than c filters but less than B filter. A bit odd. •	• Seems better to model low k starter dyke as a boundary condition. • Main problem is getting the boundary conditions for multiple filters to work. Took all day. • $k_h = 16 \times 10^{-4}$ cm/s • $k_{PF} = 1 \times 10^{-3}$ cm/s • Still not entirely satisfied. • POOR
E85+00	MLSB Cell 18	• Complex geometry of a short beach (350 m), underlain by sand and muskeg at toe, starter dyke on muskeg, three filters operating. • D filter showing more flow than C filters but less than B filter. A bit odd. • Basal aquifer not really modelled.	• Complex. Took all day. • $k_h = 7 \times 10^{-4}$ cm/s • $k_v/k_h = 1$ • Still not entirely satisfied. • POOR

Section	Location	Geometry / geology notes	Analysis notes
E88+00	MLSB Cell 18	• Underlain by aquitard throughout • Low overall slope angle • Large tailings sand toe berm • D level and 'B' Level filters active • Long beach (700 m)	• Fairly straightforward • Good match on piezometers • $k_v/k_h = 0.1$ • $k_h = 10 \times 10^{-4}$ cm/s. • GOOD
E95+00	MLSB Cell 17	• Underlain by aquitard throughout • Low overall slope angle (30H:1V) • Large tailings sand toe berm • D level and 'B' Level filters. • Long beach (900 m)	• Fairly straightforward • Never could quite get phreatic as high as measured (4m shy) but otherwise not too bad. • Divide on the beach – pond is net discharge. • $k_v/k_h = 0.1$ • $k_h = 2.5 \times 10^{-4}$ cm/s. • FAIR
E102+00	MLSB Cell 16	• Long beach (1100 m) • B filter only is active • Long toe berm • Not entirely sure of flows due to blocked cells	• Took quite a while to analyze • Good match with piezometers and fluxes • $k_h = 7 \times 10^{-4}$ cm/s • FAIR
W04+00	MLSB Cell 1	• Medium length beach (500 m) • Most flux from B filter, some from A • Steep downstream face • Underlain by thin Pf under centre part of downstream face	• $k_h = 4 \times 10^{-4}$ cm/s • $k_{PF} = 1 \times 10^{-3}$ cm/s • GOOD
W10+00	MLSB Cell 2	• Underlain by Ho aquifer under toe • Short beach (200 m) • High slope, high gradient • High flux • Small fluxes from C and A, most flux from B filter.	• Straightforward, well behaved • $k_h = 3.2 \times 10^{-4}$ cm/s • $k_v = 3 \times 10^{-3}$ cm/s • GOOD
W15+00	MLSB Cell 3	• Corner of the deposit – rapidly expanding near toe • Ho layer underneath – may be acting as underdrain • Moderately steep, three filters, medium-length beach.	• $k_h = 2 \times 10^{-4}$ cm/s • If the H_o is low permeability, then the permeability comes out at 1.5 vs 2.8 if it is very permeable. • Problems with this section because it is the outside corner – expanding flow path. • Expanding flow path means the lowest filter (B) is dry. • POOR
W20+00	MLSB Cell 4	• Sort of a corner effect. • aquitard throughout, there may be some influence from Ho layer (not modelled) • Moderately steep slope (make a table)	• $k_h = 2 \times 10^{-4}$ cm/s • Fairly easy match, never does match piezo under crest. • Ho modelled as impermeable. Could be an aquifer.

Section	Location	Geometry / geology notes	Analysis notes
			• Standpipes show high water table near c drain but now flow. This analysis lumps together C and B flow to make the balance. • K_v/K_h ratio 1/10 • FAIR
W26+00	MLSB Cell 4	• Corner geometry may be important. • Underlain by aquitard throughout • Low overall slope angle • Large tailings sand to berm (south limit) • Short beach (00 m) • D level and 'B' Level filters.	• Water table higher than predicted. • If ratio = 16 k_h=5x10^{-4} cm/s. • If ratio = 100 k_h=6x10^{-4} cm/s • Pore-pressures 4m higher than predicted. • Good matching of D and B filters. • Might be able to lower water table with lower percolation rate (seems to be a natural location) • FAIR
W31+00	MLSB Cell 5	• Underlain by aquitard throughout • Low overall slope angle • Large tailings sand toe berm • Single filter ('B' Level) • Short beach (250 m)	• Analyzed first time – easy • Good match to water table • k_h = 8 x 10^{-4} cm/s • GOOD
W37+00	MLSB Cell 6	• Underlain by aquitard throughout • Low overall slope angle • Large tailings sand toe berm • Single filter ('B' Level) • Short beach (100 m)	• Straightforward • Calculated WT a little lower than measured except on beach • High fluxes where beach short. • k_h= 7 x 10^{-4} cm/s • GOOD
W43+00	MLSB Cell 6/7 West side	• Underlain by aquitard throughout • Low overall slope angle (24H:1V) • Large tailings sand toe berm • Single filter ('B' Level) • Short beach (160 m)	• Straightforward • Relatively easy to match performance data • k_h= 4 x 10^{-4} cm/s • GOOD
W55+00	MLSB Cell 8	• Underlain by aquitard throughout • Low overall slope angle • Large tailings sand toe berm • Single filter ('B' Level) • Short beach (130 m)	• Straightforward • Relatively easy to match performance data • k_h= 2.2 x 10^{-4} cm/s • GOOD
W61+00	MLSB Cell 9	• Underlain by aquitard throughout • Low overall slope angle (24H:1V) • Large tailings sand toe berm • Single filter ('B' Level) • Short beach (160 m)	• A bit difficult • Fair match with data. • k_h= 4 x 10^{-4} cm/s • FAIR
W67+00	MLSB Cell 10	• Underlain by aquitard throughout	• Never quite able to match high water table (3m too low)

Section	Location	Geometry / geology notes	Analysis notes
		• Low overall slope angle • Large tailings sand toe berm • Single filter ('B' Level) • Medium beach (300 m)	• k_h= 4 x 10^{-4} cm/s • FAIR
W72+00	MLSB Cell 11	• Underlain by aquitard throughout • Low overall slope angle (30H:1V) • Large tailings sand toe berm • Single filter ('B' Level) • Long beach (750 m)	• Fairly difficult to analyze • Needed to increase percolation rate on bare beach to 40% • Never quite able to match very high water table • Seems to be a divide on the beach – rainfall percolates back to pond. • Section has a lot of similarities to SWSS • Kv/Kh = 1 • k_h= 4 x 10^{-4} cm/s. • POOR
W79+00	MLSB Cell 12	• Underlain by aquitard throughout • Blocked by CT Prototype at toe • Corner topography (not factored) • Single filter ('B' Level) • Very long beach (1300 m)	• Perhaps the easiest of all to analyzed. Filter flows and heads all matched on first try. • k_h=8 x 10^{-4} cm/s • Most water is from beach infiltration • Strong horizontal component to unsaturated flow • GOOD
W100+50	MLSB Cell 16	• Underlain by aquitard throughout • Low overall slope angle • Large tailings sand toe berm • D level and 'B' Level filters. • Long beach (1000 m) • Adjacent filters blocked, unsure of real flux per m	• Fairly difficult • k_h= 35 x 10^{-4} cm/s. • Kv/Kh=0.01 • POOR
SWSS (Based on Oct 1999 profile.)			
SWSS Cell 31	SWSS Cell 31	• All beaches about the same length (700 m) for these SWSS analyses • All beaches and downstream slopes similar angles • 20% percolation on slopes, 40% on beach • Highest slope (37m) and longest downslope. • Starter berm	• Easy • k_h= 8 x 10^{-4} cm/s • Good match with standpipes • Divide 500 m down beach • Flux near toe estimated at 0.16m^3/m/day • Flux at crest estimated at 0.24 m^3/m/day • GOOD
SWSS Cell 48	SWSS Cell 48	• Lowest height (24m) and shortest slope. • Underlain by very permeable leaky Pleistocene channel, imperfectly	• Numerical stability challenges. • Easy to get good match. • Wildly affected by leaky aquifer – seepage back analysis almost

Section	Location	Geometry / geology notes	Analysis notes
		capped. Poorly defined.	unconstrained, geometry of aquifer poorly defined. • Divide about 500 m down beach • Large unsaturated zone • Flux neat toe estimated at $0.35m^3$/m/day • k_h= 8 x 10^{-4} cm/s • POOR
SWSS Cell 49	SWSS Cell 49	• Small starter berm	• Some difficulty with boundary conditions for percolation. • Minor changes in properties changes whether flow is upwards or downwards in pond. • Flux neat toe estimated at $0.28m^3$/m/day • k_h= 10 x 10^{-4} cm/s • FAIR • Had to adjust heal of first bench. Seep/W having problems with multiple seepage faces with review boundaries.
SWSS Cell 51	SWSS Cell 51	• High slope • Modest starter berm	• $0.32m^3$/m/day • Divide about 500 m down beach • k_h= 6 x 10^{-4} cm/s • GOOD

Appendix E

Database of erosion flume trial measurements

Trial	Soil type	Water type	Fresh or recirculating water	Avg slope %	Soil length cm	Soil width cm	Soil area m2	Init soil moist	Avg flow rate lpm	Avg flow width cm	Avg flow depth, mm	Avg eroding area m2	Avg shear stress Pa	Avg water velocity cm/s	Avg Manning roughness, N	Elapsed time hh:mm 1	Elapsed time hh:mm 2	Elapsed time hh:mm 3
401	30 dump	Tap	R	1.1	266	21	0.56	22%	2	17	3.5	0.46	0.5	6	0.044	00:05	00:24	00:54
402	30 dump	Tap	R	1.1	266	19	0.49	23%	18	17	10.0	0.47	0.9	17	0.026	00:02	00:13	00:30
403	30 dump	Tap	R	2.6	266	19	0.52	23%	17	16	11.0	0.41	2.0	15	0.044	00:04	00:16	00:46
406	30 dump	Tap	R	4.9	266	20	0.54	26%	31	20	8.2	0.54	3.8	32	0.027	00:02	00:08	00:37
404	30 dump	Tap	R	9.9	266	6	0.16	22%	9	6	6.2	0.16	4.9	43	0.025	00:02	00:10	00:34
405	30 dump	Tap	R	20.5	266	6	0.16	23%	13	6	4.3	0.16	8.7	84	0.013	00:03	00:10	00:30
449	30 dump	Tap	R	20.1	266	19	0.51	20%	38	16	5.7	0.43	10.3	72	0.020	00:02	00:08	00:30
407	30 dump	CT	R	0.8	266	19	0.51	21%	2	19	3.8	0.51	0.3	5	0.041	00:03	00:10	00:33
408	30 dump	CT	R	1.0	266	19	0.50	24%	18	19	8.1	0.50	0.7	21	0.020	00:02	00:10	00:31
409	30 dump	CT	R	2.5	266	19	0.50	20%	34	14	9.8	0.37	2.5	27	0.016	00:03	00:11	00:30
410	30 dump	CT	R	4.9	266	19	0.51	19%	17	16	8.0	0.41	3.0	23	0.036	00:02	00:10	00:30
411	30 dump	CT	R	10.1	266	19	0.50	20%	10	19	4.1	0.51	4.0	25	0.036	00:03	00:10	00:30
412	30 dump	CT	R	20.3	266	19	0.51	19%	30	19	4.3	0.51	7.3	77	0.019	00:02	00:12	
413	30 dump	RCW	R	0.7	266	19	0.51	23%	3	18	7.2	0.48	0.5	4	0.087	00:03	00:10	00:28
414	30 dump	RCW	R	1.1	266	19	0.50	23%	16	19	8.5	0.50	0.9	17	0.025	00:02	00:13	00:33
415	30 dump	RCW	R	3.2	266	19	0.51	23%	10	13	6.8	0.34	2.2	17	0.030	00:04	00:10	00:30
416	30 dump	RCW	R	4.8	266	19	0.50	23%	14	17	7.5	0.46	3.5	18	0.044	00:04	00:11	00:31
417	30 dump	RCW	R	10.1	266	19	0.50	23%	28	19	11.5	0.50	10.6	23	0.070	00:03	00:10	00:35
418	30 dump	RCW	R	19.6	266	19	0.50	23%	31	17	10.0	0.44	16.9	30	0.062	00:02	00:10	00:30
419	30 dump	Tap+Lime	R	0.5	266	19	0.51	23%	2	19	11.8	0.51	0.6	2	0.197	00:02	00:10	00:30
420	30 dump	Tap+Lime	R	1.0	266	19	0.50	24%	15	19	23.4	0.50	2.0	6	0.126	00:02	00:10	00:29
421	30 dump	Tap+Lime	R	2.2	266	19	0.50	23%	9	19	11.6	0.50	2.4	7	0.106	00:02	00:10	00:31
441	30 dump	PP	R	5.0	266	19	0.51	22%	17	19	7.4	0.51	3.5	22	0.040	00:02	00:10	00:30
442	30 dump	Tap+Lime	R	20.0	266	19	0.51	22%	38	14	3.8	0.37	7.5	113	0.009	00:02	00:10	00:30
422	30 dump	DW	R	4.9	266	19	0.50	25%	18	16	7.8	0.42	3.5	26	0.032	00:03	00:15	00:32
424	30 dump	DW	R	20.1	266	19	0.50	23%	25	18	6.2	0.47	11.2	49	0.038	00:02	00:10	00:35
425	30 dump	DW	R	0.7	266	19	0.51	22%	3	19	7.3	0.51	0.4	3	0.090	00:02	00:12	00:29
426	30 dump	DW	R	1.0	266	19	0.50	24%	15	19	11.6	0.50	1.2	11	0.040	00:02	00:12	00:29
427	30 dump	DW	R	2.4	266	19	0.50	22%	9	18	6.3	0.49	1.5	13	0.037	00:02	00:10	00:30
429	30 dump	DW	R	9.8	266	19	0.50	21%	30	19	7.9	0.50	7.2	35	0.035	00:02	00:12	00:30
438	30 dump	Tap	F	0.9	266	19	0.51	22%	13	19	11.7	0.51	1.1	9	0.049	00:02	00:10	00:30
428	30 dump	Tap	F	4.7	266	19	0.50	23%	13	10	8.8	0.26	3.8	20	0.033	00:02	00:10	00:34
423	30 dump	Tap	F	9.7	266	19	0.50	22%	13	14	6.1	0.37	4.9	24	0.040	00:02	00:11	00:33
448	30 dump	Tap	F	20.0	266	19	0.51	20%	13	11	6.1	0.30	11.2	29	0.044	00:02	00:10	00:30
431	30 dump	PP	R	1.0	266	19	0.51	22%	4	19	8.6	0.51	0.9	4	0.099	00:03	00:10	00:28
432	30 dump	PP	R	1.0	266	19	0.51	23%	18	19	13.6	0.51	1.3	12	0.044	00:02	00:10	00:30

Trial	Soil type	Water type	Fresh or recirculating water	Avg slope %	Soil length cm	Soil width cm	Soil area m2	Init soil moist	Avg flow rate lpm	Avg flow width cm	Avg flow depth, mm	Avg eroding area m2	Avg shear stress Pa	Avg water velocity cm/s	Avg Manning roughness, N	Elapsed time hh:mm 1	Elapsed time hh:mm 2	Elapsed time hh:mm 3
433	30 dump	PP	R	2.5	266	19	0.51	22%	11	19	6.2	0.51	1.6	15	0.034	00:02	00:10	00:30
434	30 dump	PP	R	4.8	266	19	0.51	23%	18	19	8.0	0.51	3.8	19	0.044	00:02	00:10	00:30
430	30 dump	PP	R	1.0	266	19	0.51	23%	36	15	6.8	0.39	11.2	54	0.006	00:02	00:10	00:30
436	30 dump	PP	R	20.0	266	19	0.51	21%	20	18	8.3	0.47	13.9	54	0.076	00:02	00:10	00:30
440	30 dump	PP	R	19.9	266	19	0.50	22%	33	19	3.9	0.50	8.0	84	0.014	00:02	00:10	00:34
437	30 dump	PP	R	1.1	266	19	0.51	22%	12	19	17.5	0.51	2.1	7	0.107	00:02	00:10	00:30
439	30 dump	PP	R	2.5	266	19	0.51	22%	11	19	11.5	0.51	2.6	9	0.090	00:02	00:10	00:32
435	30 dump	PP	R	20.2	266	19	0.51	22%		19		0.51				00:00		
443	30 dump	PP	R	1.1	266	19	0.51	21%	2	10	5.7	0.26	0.7	15	0.044	00:02	00:10	00:30
444	30 dump	PP	R	1.1	266	19	0.51	21%	17	19	10.3	0.51	1.1	14	0.032	00:02	00:10	00:30
445	30 dump	PP	R	2.4	266	19	0.51	21%	10	19	7.5	0.51	1.7	13	0.047	00:02	00:11	00:30
446	30 dump	PP	R	5.0	266	19	0.51	20%	3	19	5.5	0.51	2.4	36	0.133	00:02	00:10	00:30
447	30 dump	PP	R	19.9	266	19	0.51	21%	34	19	3.4	0.51	6.3	98	0.011	00:02	00:10	00:32
501	30 dump 2	WID	F	1.0	266	19	0.50	18%	5	19	8.4	0.50	0.9	5	0.079	00:02	00:10	00:30
502	30 dump 2	WID	F	0.8	266	19	0.50	18%	17	19	11.6	0.50	0.9	13	0.032	00:02	00:11	00:30
503	30 dump 2	WID	F	3.1	266	19	0.50	18%	14	12	10.6	0.31	3.0	16	0.040	00:02	00:10	00:30
504	30 dump 2	WID	F	5.9	266	19	0.50	18%	15	11	9.3	0.29	4.5	27	0.039	00:02	00:10	00:30
505	30 dump 2	WID	F	9.8	266	19	0.50	18%	31	16	7.5	0.42	6.8	37	0.026	00:02	00:10	00:30
506	30 dump 2	WID	F	19.4	266	19	0.51	18%	36	17	6.8	0.46	13.0	46	0.029	00:02	00:10	00:30
507	30 dump 2	WID	R	1.2	266	19	0.50	16%	3	19	7.0	0.50	0.9	3	0.120	00:02	00:10	00:30
508	30 dump 2	WID	R	0.8	266	19	0.50	15%	12	19	13.7	0.50	1.0	11	0.060	00:02	00:10	00:30
509	30 dump 2	WID	R	2.2	266	19	0.50	15%	9	18	10.7	0.49	1.9	10	0.088	00:02	00:12	00:33
510	30 dump 2	WID	R	5.4	266	19	0.51	17%	17	13	6.4	0.35	3.1	32	0.023	00:02	00:10	00:30
511	30 dump 2	WID	R	10.8	266	19	0.51	17%	31	19	6.4	0.51	5.0	63	0.026	00:02	00:10	00:30
513	30 dump 2	WID	R	19.2	266	19	0.51	13%	32	17	6.4	0.46	10.6	55	0.030	00:02	00:10	00:30
514	PI	WID	F	1.1	266	19	0.51	14%	7	19	9.5	0.51	0.9	7	0.066	00:02	00:10	00:30
515	PI	WID	F	2.7	266	19	0.50	13%	17	19	7.6	0.50	2.0	20	0.030	00:02	00:10	00:15
516	PI	WID	F	1.1	266	19	0.51	11%	13	19	10.7	0.51	1.1	11	0.044	00:02	00:10	00:30
517	PI	WID	F	5.5	266	19	0.50	13%	17	19	7.0	0.50	3.7	23	0.037	00:02	00:10	00:30
518	PI	WID	F	10.0	266	19	0.52	14%	34	18	7.1	0.47	6.1	47	0.024	00:02	00:12	00:33
519	PI	WID	F	20.4	266	19	0.52	14%	36	16	7.3	0.42	13.8	51	0.031	00:02	00:10	00:30
520	Marie Kc	WID	F	1.0	266	19	0.50	27%	5	19	11.2	0.50	1.1	4	0.122	00:02	00:10	00:30
521	Marie Kc	WID	F	1.2	266	19	0.50	27%	14	19	12.1	0.50	1.4	10	0.051	00:02	00:10	00:30
522	Marie Kc	WID	F	2.5	266	19	0.50	27%	11	19	10.3	0.50	2.4	10	0.071	00:02	00:10	00:30
523	Marie Kc	WID	F	5.5	266	19	0.50	26%	19	13	9.7	0.34	5.1	26	0.038	00:02	00:10	00:30
524	Marie Kc	WID	F	9.0	266	19	0.51	27%	37	17	9.2	0.46	6.7	44	0.032	00:02	00:10	00:30

Trial	Soil type	Water type	Fresh or recirculating water	Avg slope %	Soil length cm	Soil width cm	Soil area m2	Init soil moist	Avg flow rate lpm	Avg flow width cm	Avg flow depth, mm	Avg eroding area m2	Avg shear stress Pa	Avg water velocity cm/s	Avg Manning roughness, N	Elapsed time hh:mm 1	Elapsed time hh:mm 2	Elapsed time hh:mm 3
525	Marie Kc	WID	F	19.7	266	19	0.51	27%	35	19	9.1	0.50	14.9	59	0.053	00:02	00:10	00:30
526	T-sand	WID	F	1.0	266	19	0.50	6%	4	19	9.8	0.50	1.1	4	0.138	00:02	00:10	00:20
527	T-sand	WID	F	1.0	266	19	0.50	6%	10	19	10.8	0.50	1.1	8	0.057	00:02	00:10	00:30
528	T-sand	WID	F	2.7	266	19	0.51	6%	18	14	11.2	0.37	2.6	19	0.039	00:02	00:10	00:30
529	T-sand	WID	F	5.7	266	19	0.51	7%	20	12	3.8	0.32	2.4	77	0.007	00:02	00:10	
530	T-sand	WID	F	9.7	266	19	0.51	6%	38	16	2.0	0.41	2.1	216	0.002	00:02		
531	T-sand	WID	F	20.9	266	19	0.51	6%	40	14	3.5	0.37	7.0	137	0.007	00:02		
532	Marie Kc	CT	R	1.0	266	19	0.50	25%	6	14	10.8	0.37	1.1	6	0.065	00:03	00:10	00:30
533	Marie Kc	CT	R	1.1	266	19	0.51	24%	15	17	15.3	0.45	1.5	11	0.062	00:02	00:10	00:30
534	Marie Kc	CT	R	2.6	266	19	0.51	24%	11	17	10.4	0.45	2.4	11	0.072	00:02	00:10	00:32
535	Marie Kc	CT	R	5.1	266	19	0.51	24%	19	13	8.9	0.34	4.0	28	0.032	00:02	00:10	00:32
536	Marie Kc	CT	R	9.5	266	19	0.51	24%	37	18	6.9	0.49	6.6	52	0.022	00:02	00:10	00:30
537	Marie Kc	CT	R	19.8	266	19	0.51	26%	31	18	6.0	0.49	13.3	51	0.030	00:02	00:10	00:30
601	Insitu 30 Dump	PP	F	8.9	4,000	17	6.93	18%	14	14	13.7	5.60	10.3	17	0.125	00:10	00:25	00:35
602	Insitu 30 Dump	PP	F	8.5	4,000	22	8.60	39%	30	17	22.6	6.64	17.3	20	0.147	00:04	00:15	00:30
603	Insitu 30 Dump	PP	F	8.4	4,000	16	6.26	17%	19	16	27.1	6.32	19.1	9	0.293	00:02	00:15	00:31
604	Insitu 30 Dump	PP	F	8.1	4,000	21	8.32	9%	9	11	19.7	4.54	12.9	7	0.255	00:03	00:20	00:43
605	Insitu 30 Dump	PP	F	5.9	4,000	21	8.28	12%	4	6	16.3	2.37	7.5	9	0.176	00:05	00:15	00:30
606	Insitu 30 Dump	PP	F	3.5	4,000	20	8.00	11%	1	10	21.4	4.00	6.0	9	1.991			
801	Insitu 30 Dump	PP	F	11.5	295	20	0.59	14%	18	9	34.1	0.25	29.4	11	0.235	00:02	00:10	00:30
802	Insitu 30 Dump	PP	F	9.9	299	22	0.65	13%	17	7	29.6	0.22	20.7	16	0.158	00:03	00:11	00:30
803	Insitu 30 Dump	PP	F	9.6	305	22	0.66	11%	6	5	18.3	0.14	14.4	14	0.126	00:02	00:10	00:33
804	Insitu 30 Dump	PP	F	6.7	304	22	0.66	9%	8	8	17.2	0.24	9.4	9	0.139	00:02	00:10	00:31
805	Insitu 30 Dump	PP	F	5.8	288	21	0.60	14%	5	9	11.7	0.27	5.6	9	0.132	00:08	00:28	00:58
806	Insitu 30 Dump	PP	F	8.4	296	19	0.57	16%	2	6	6.5	0.17	4.8	11	0.123	00:16	00:28	00:58

Trial	Elapsed time hh:mm 4	Elapsed time hh:mm 5	Elapsed time hh:mm 6	Solids content of total discharge, % solids 2 minutes	Solids content of total discharge, % solids 10 minutes	Solids content of total discharge, % solids 30 minutes	Solids content of total discharge, % solids 60 minutes	Solids content of total discharge, % solids 180 min	Solids content of total discharge, % solids 300 min	Final dry solids in garbage can kg	Final moisture content, top layer, % solids	Final moisture content, middle layer, % solids	Final moisture content, bottom, % solids
401	02:28	03:40	04:42	0.06	0.07	0.04	0.05	0.05	0.06	0.00	56	65	79
402	01:15	03:05	03:49	0.07	0.10	0.16	0.30	0.62	0.67	0.10	60	66	78
403	01:46	04:43		0.17	0.56	0.77	1.09	1.56		0.30	63	67	77
406	01:02	04:04		0.33	0.47	0.77	1.26	2.57		3.07	66	70	75
404	01:08	02:00		0.27	0.22	0.31	0.44	0.63		1.09	75		79
405	01:00	02:08		0.18	0.20	0.29	0.46	0.81		1.23	77		69
449	01:00	03:00	05:00	1.41	1.28	1.52	2.09	3.89	4.73	9.44	69	69	81
407	01:00	03:01	05:00	0.19	0.20	0.22	1.61	1.65	1.66	0.00	56	62	65
408	00:59	03:00	05:00	0.22	0.31	0.37	0.45	0.48	0.56	0.27	56	70	
409	01:00	03:00	04:38	1.03	1.08	1.07	1.14	2.06	2.50	4.83	67	69	69
410	01:00	03:00	04:01	1.03	0.88	1.19	1.51	2.69	2.82	8.11	67	70	70
411	01:00			2.56	1.29	1.52	1.81			3.09	72	74	81
412				2.10	1.67					3.11	67	81	78
413	01:01	03:00	05:00	0.21	0.15	0.16	0.20	0.22	0.17	0.04	58	66	72
414	01:00	03:00	05:05	0.22	0.30	0.38	0.43	0.46	0.45	0.19	60	71	68
415	01:00	02:58	05:04	0.39	0.39	0.60	0.67	0.77	0.77	0.67	64	68	70
416	01:00	03:00	05:00	0.83	0.60	0.62	0.71	0.72	0.85	1.19	64	69	71
417	01:00	03:00	04:52	0.62	0.82	0.95	1.13	1.54	1.94	2.19	69	72	75
418	01:00	03:00	04:40	0.85	0.98	1.44	1.83	2.52	3.15	3.72	68	72	77
419	01:00	03:00	05:00	0.16	0.17	0.21	0.14	0.12	0.14	0.03	53	62	60
420	01:01	03:00	05:00	0.30	0.32	0.30	0.24	0.15	0.18	0.19	53	62	66
421	01:00	03:01	04:55	0.29	0.28	0.31	0.25	0.26	0.15	0.17	56	66	68
441	01:00	03:03	05:03	0.38	0.44	0.57	0.50	0.34	0.12	1.77	60	79	62
442	01:00	03:00		0.48	0.53	0.98	1.53	5.82		9.55	70	71	72
422	01:00	03:00	05:00	0.52	1.11	1.57	1.81	1.77	1.80	1.02	65	73	74
424	01:04	03:00	05:01	1.32	2.08	3.58	4.03	5.09	5.78	4.62	69	71	77
425	00:59	03:01	04:59	0.06	0.07	0.06	0.07	0.06	0.06	0.01	62	69	70
426	01:00	03:00	05:00	0.12	0.16	0.30	0.32	0.31	0.32	0.04	61	69	72
427	01:00	03:00	05:01	0.29	0.40	0.50	0.54	0.65	0.59	0.29	61	69	69
429	00:59	03:00	05:00	0.74	1.84	2.50	2.80	3.33	3.54	2.03	73	69	71
438	01:00	03:00	05:00	0.06	0.05	0.04	0.06	0.04	0.04	0.32	66	71	73
428	01:18	03:00	05:00	0.28	0.27	0.15	0.19	0.22	0.16	5.78	68	71	70
423	01:03	03:00		0.29	0.30	0.22	0.64	0.73		5.64	69	73	74
448	01:00	02:05		1.53	1.25	0.41	0.63	0.30		9.09	70	74	75
431	01:00	03:00	05:00	0.05	0.05	0.05	0.07	0.05	0.15	0.01	63	70	73
432	01:00	03:00	05:00	0.10	0.10	0.16	0.18	0.19	0.20	0.05	65	70	73

Trial	Elapsed time hh:mm 4	Elapsed time hh:mm 5	Elapsed time hh:mm 6	Solids content of total discharge, % solids 2 minutes	Solids content of total discharge, % solids 10 minutes	Solids content of total discharge, % solids 30 minutes	Solids content of total discharge, % solids 60 minutes	Solids content of total discharge, % solids 180 min	Solids content of total discharge, % solids 300 min	Final dry solids in garbage can kg	Final moisture content, top layer, % solids	Final moisture content, middle layer, % solids	Final moisture content, bottom, % solids
433	01:01	03:00	05:01	0.13	0.24	0.35	0.43	0.48	0.48	0.26	69	69	62
~~434~~	01:00	03:00	05:00	0.79	0.71	0.81	0.89	1.10	1.34	2.15	68	72	72
430	01:00	03:00	05:00	0.86	1.39	2.10	2.70	4.28	5.11	7.42	70	71	71
436	01:00	03:00	05:00	1.42	1.76	2.76	2.59	4.36	6.18	1.20	74	73	75
440	01:00	03:00	05:00	0.56	0.88	1.58	1.88	2.64	3.15	1.23	71	72	76
437	01:00	03:00	05:00	0.07	0.08	0.13	0.14	0.15	0.18	0.00	64	64	58
439	01:00	03:00	05:00	0.15	0.18	0.27	0.26	0.26	0.24	0.10	61	63	61
435										0.00			
443	01:00	03:01	05:00	0.07	0.08	0.11	0.12	0.13	0.12	0.08	63	74	71
444	01:01	03:00	05:26	0.07	0.13	0.23	0.32	0.31	0.32	0.15	64	64	75
445	01:00	03:00	05:00	0.12	0.23	0.34	0.39	0.37	0.35	0.17	63	68	73
446	01:00	03:00	05:00	0.40	0.65	#N/A	1.43	1.44	1.48	1.20	68	72	77
447	01:00	03:00	05:00	0.71	1.02	1.59	1.95	2.55	3.17	3.39	70	71	75
501	01:00	03:00	05:00	0.03	0.02	0.02	0.02	0.03	0.03	0.04	66	73	74
502	01:00	03:00	05:00	0.04	0.02	0.03	0.03	0.03	0.02	0.11	59	73	72
503	01:00	03:00	05:00	0.12	0.20	0.16	0.16	0.06	0.09	0.82	67	71	70
504	01:00	03:00	05:00	0.36	0.22	0.23	0.12	0.16	0.05	5.03	69	68	70
505	01:00	03:00		0.70	0.25	0.20	0.25	0.08		5.50	65	77	75
506	01:02	03:06		0.79	0.52	0.47	0.36	0.10		9.09	75	79	82
507	01:00	03:00	05:00	0.04	0.05	0.04	0.09	0.05	0.04	0.03	63	72	71
508	01:00	03:00	05:00	0.07	0.06	0.06	0.04	0.04	0.05	0.52	64	71	74
509	01:00	03:00	05:00	0.46	0.23	0.30	0.25	1.07	1.26	1.88	68	72	71
510	01:00	03:00	05:00	0.38	0.25	0.23	0.22	0.15	0.24	6.68	68	72	73
511	01:02	03:00	05:00	0.82	0.56	0.60	0.56	1.06	1.64	4.73	70	71	73
513	01:00	03:00		0.44	0.22	0.25	0.26	0.62		10.85	71	74	74
514	01:00	03:00	05:00	0.04	0.03	0.07	0.05	0.03		0.00	87	85	79
515	01:00	03:00		0.37	0.41	0.19	0.08	0.05		0.00	76	81	85
516	01:00	03:00		0.04	0.03	0.03	0.02	0.03		0.02	77	85	84
517	01:00	03:00		0.87	0.50	0.16	0.09	0.11		1.77	77	83	83
518	01:02	03:00		1.12	0.42	0.71	0.11	0.10		4.45	80	87	87
519	01:00	03:00		0.71	0.47	0.34	0.18	0.20		3.03	78	84	86
520	01:00	03:00	05:00	0.02	0.02	0.01	0.08	0.07	0.08	0.61	57	61	64
521	01:00	03:00	05:00	0.03	0.02	0.04	0.04	0.02	0.09	0.60	57	62	70
522	01:00	03:00	05:01	0.07	0.05	0.18	0.12	0.06	0.11	1.09	58	62	66
523	01:00	03:00		0.23	0.32	0.26	0.35			6.21	59	65	67
524	01:01			0.93	0.59	0.70	0.47			9.85	63	70	76

Trial	Elapsed time hh:mm 4	Elapsed time hh:mm 5	Elapsed time hh:mm 6	Solids content of total discharge, % solids 2 minutes	Solids content of total discharge, % solids 10 minutes	Solids content of total discharge, % solids 30 minutes	Solids content of total discharge, % solids 60 minutes	Solids content of total discharge, % solids 180 min	Solids content of total discharge, % solids 300 min	Final dry solids in garbage can kg	Final moisture content, top layer, % solids	Final moisture content, middle layer, % solids	Final moisture content, bottom, % solids
525	01:00			1.83	0.81	0.26	0.22			6.78	62	75	76
526	01:00	03:00	05:00	0.03	0.02	0.03	0.03	0.03	0.03	0.17	79	82	82
527	01:00	03:00	05:00	0.04	0.03	0.05	0.06	0.04	0.03	0.84	78	80	81
528	01:00	01:15		0.83	1.68	1.37	0.96			5.89	81	81	80
529				6.58	3.71					11.56	78	79	82
530				10.53						10.72	78	80	79
531				32.81						12.77	86	88	86
532	01:00	03:00	05:00	0.11	0.12	0.14	0.08	0.12	0.13	0.86	62	61	58
533	01:00	03:00	05:00	0.17	0.15	0.22	0.22	0.69	1.17	0.96	58	62	65
534	01:00	03:00	05:00	0.28	0.63	0.42	0.92	2.12	2.11	0.86	61	65	67
535	01:00	03:00		0.73	0.84	2.65	2.74	2.68	1.66	1.76	59	64	65
536	01:00				1.33	2.63	3.51			1.28	64	67	70
537	01:00	03:00		9.73	2.67	2.92	3.69	6.39		9.18	64	65	67
601	01:00	03:10	05:00	9.92	21.76	6.84	0.76	0.86	0.48		62	69	64
602	00:50	03:00	05:00	16.16	8.25	4.29	1.65	1.18			70	74	74
603	01:04	03:05	05:00	8.81	4.58	8.05	1.34	2.18	2.53		75	76	
604	01:10	03:05		6.12	4.34	3.63	2.55	0.79			68	81	
605	01:00	03:00	05:00				4.38	2.44	1.47		67	74	
606	01:57	04:00						4.31	0.40		76	64	
801	01:00	03:00	05:03	2.44	0.58	0.43	0.28	0.30	0.13		71	68	76
802	01:00	02:55	05:00	5.43	2.16	0.61	0.78	0.30	0.41		71	72	69
803	01:00	03:00	04:09	5.26	4.44	0.87	0.87	0.73	0.37		69	71	73
804	01:02	02:58		0.87	1.02	0.98	0.64	0.69			66	72	
805	01:00			1.38	1.90	2.66	0.70				71	58	
806	02:42	02:44		2.24	1.56	1.33	0.77	0.30			65	70	73